AN APPROACH TO A FIELD DRAINAGE PROBLEM BY LABORATORY EXAMINATION OF SELECTED PROPERTIES OF UNDISTURBED SOIL CORES.

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by

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- 1964 -

The results on hydraulic studies reported herein represent the partial repetition of a more exhaustive study, all records of which were completely destroyed by a fire arising from an electrical defect in the laboratory. This loss has limited the drawing of conclusions and must be taken into account in evaluating the work.

CVFife
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SECTION A

INTRODUCTION

For many years, soil drainage investigators, from a practical view point, have had to content themselves with expert appraisal of certain direct and indirect soil and environmental characteristics in order to ascertain the cause of a particular drainage problem. In a great many instances, observations of vegetative composition, topography and general soil type, aided by aerial photography and local experience, give completely adequate information. Normally, derivation of conclusions from such observations is based on well established principles, and the recognition of general broad classes of the cause of mal-drainage conditions. Such classes may be grouped as; (I) where infiltration capacity of a soil is inadequate to deal with the amount of water supplied to the surface, because of topography, abnormal rainfall, or through inherent inability of the soil to transmit water internally, (II) where the ground-water table rises to a height detrimental to vegetative survival and/or soil structure, or where its presence hinders the function of a free draining subsoil, and (III) where a similar situation exists, due to a perched or elevated ground-water table.

The allocation of a particular drainage problem to one or more of these broad classes is not usually difficult, but identification of causal processes within classes presents quite another problem. Often, drainage investigators have been content to evolve general treatments for each class, and, as a basic rule, such procedures have, more often than not, proved reasonably effective. However, with the increasing intensification of pastoral and agricultural farming, the fundamental causes of individual mal-drainage conditions must be positively identified and rectified within the broadly classified groups.

In many parts of the world, significant steps have been taken in this direction, especially within group (I) above. Here again, investigators pursue two different approaches; (a) indirect analysis of physical properties of soils, related, more or less, to the ability of the soil to transmit water, and (b) direct analysis of the hydraulic transmitting power of soils. The first approach includes critical examination of such factors as the following:

Type of structure
Grade (stability) of structural aggregates
Relative length of horizontal and vertical axes of structural aggregates
Texture
Comparative ease and direction of natural breakage

Size and number of visible pores, cracks and channels, visible under a hand lens

Character of clay minerals

Compaction

Size and shape of sand grains

Mottling

Organic Material

Soluble salts

While evaluation, on a basis of the above characteristics may be, in many instances, convenient and relatively non time-consuming, O'Neal (1949), the joint proposer of the above list (1951), stressed that few factors individually could be considered good guides to intrinsic permeability. Rather, all factors should be considered singularly and in relation to one another, and even then the correlation with intrinsic permeability is not always entirely satisfactory.

The second approach involves measuring, directly, certain fundamental physical properties of the soil as a means of establishing causes of low intrinsic permeability. Among the workers involved in direct measurements, two general approaches are again apparent. There are those who measure permeability rates in the field. Their methods include various single "auger hole" determinations, pumping between two auger holes, piezometer tube installation, infiltrometers, watershed balance sheets, and rainfall simulators. The other approach to direct measurements is to study the permeability of the profile in the laboratory, thus obviating the only real practical disadvantage of field determinations - that of the inconvenience of providing equipment in situ, in the field. These two approaches are, however, more closely related in their objectives than most, as the prime object of the laboratory techniques is to determine intrinsic permeability values that will be directly related and applicable to the field determinations. The latter, per se, must be applicable to the practical application of drainage techniques.

Under certain conditions, the traditional methods of drainage investigations may suffice, whereas under other conditions the more fundamental studies may be required. However, as increasing instances of the more difficult problems are encountered, such as in gley podsols, some Northern podsolised Yellow Brown Earths and many recent alluvial soils, the emphasis on investigation must swing more from the subjective and empirical assessments towards the attainment of direct experimental evidence based on scientific approach. It is therefore imperative that experimental techniques be evolved which enable investigators to objectively study the hydraulic characteristics of soils in order to ascertain precisely the causes of individual drainage problems.

SECTION B

REVIEW OF THE LITERATURE

The relevant literature is reviewed under the following headings:-

I Techniques for obtaining "undisturbed" soil samples.

II The transportation, storage, and preparation of soil samples prior to laboratory investigations of hydraulic characteristics.

III Supplementary laboratory equipment associated with hydraulic studies of "undisturbed" soil samples.

IV The laboratory study of water flow through "saturated" soil.

V Soil and fluid properties responsible for variations in intrinsic permeability.

VI Methods of indirect assessment of intrinsic permeability.

I TECHNIQUES FOR OBTAINING "UNDISTURBED" SOIL SAMPLES

The method of sampling varies with the specific intended use of the sample, and the equipment and facilities available. The general approaches which have been adopted by investigators may be classified as:

(a) those entailing the use of hand tools for shaping samples from the face of an exposed portion of a profile

(b) those utilizing varied forms of portable cylindrical apparatus forced vertically, by hand or mechanically assisted means, into the soil by hammering action or uniform pressure from above

(c) those utilizing varied forms of portable cylindrical apparatus, the entry into the soil being assisted by mechanically or hand motivated rotary action.

(a) The literature contains few references dealing specifically with this method of sampling, the main requirements being suitable tools, containers, and patience. Cline (1944) listed certain standards that should be adhered to to maximise the chance of satisfactory results from the examination and analysis of the samples. He stated that it was generally agreed that sampling tools should permit taking a sample unit that is (i) uncontaminated, (ii) approximately uniform in cross section to the desired depth, and (iii) reproducible. The choice of tools is with the investigator, but the principal types used by Cline (loc. cit.) were trowels, spades, shovels, spoons and knives.

Samples may be shaped from extracted large clods, the final shape being to the mould of a suitable transporting container (Gerdel 1939). He claimed that neither the technique nor the equipment required for preservation of these core samples was complicated, adding that short sections of 2 inch galvanized sheet iron proved satisfactory for collecting and holding samples. The recommended practical length for cores obtained in this manner was 2 - 3 inches.

Alternatively, cores may be shaped from a sliced face of a clean fresh vertical cut between limits of depth chosen (Cline 1944). He considered road cuts and similar excavations as being unsuitable faces for this purpose because of contamination. More desirable were freshly excavated pits that did not extend below the ground water table. Such sampling, he felt, then permitted supplementary examination of the existing profile. Cline (loc. cit.) noted that the procedure was labour and time consuming, and the restriction it imposed on numbers of samples more than offset any advantages it may have had over other methods. However, Fitzpatrick (1956) published a full description of a procedure for the collection and preservation of profile blocks for mounting. This instructed the worker to shape a block out of the trimmed vertical face of a pit, and to fit a lidless box over it, after which the whole was cut away from the wall. The original block was finally shaped in the laboratory. The main difficulties encountered with this procedure were with (i) hard or stony soils which made it hard for the box to be "cut in", and (ii) very friable soils (such as sands) which crumbled and fell both when the box was being "cut in" and when it was being cut away from the bank. Fitzpatrick (loc.cit.) felt that alternatives to this method such as a combination of the mounting process and a collection technique described by Smith and Moodie (1947) were subject to excessive risk of damage in transportation, making them less preferable to his method.

(b) A great many workers have used, devised and modified various forms of the "push in" or"hammer" type sampling tubes (Fife 1944, Lutz 1947, Steinbrenner 1950, Benz et al 1959, Burnett 1961, Keefer and Ward 1961, Thames and McReynolds 1961, Palm and Sykes 1962, Wit 1962, Boehle et al 1963).

Wit (loc.cit.) stated that, in general, the process of obtaining cores from coherent deposits presented few difficulties. By one means or another, the core barrel was first pushed into the layer(s) to be sampled and then pulled up. The friction resistance between sample and sample tube, as well as the cohesive force of the grains acting on each other, prevented core losses during the raising of the coring apparatus. Often the core barrel was shut off and made air tight above the sample by means of a piston or ball valve. The fractured cores commonly caused by hand held rotary samplers, and the shattered or compressed cores common with drive samplers, were eliminated by Thames & McReynolds (1961). They claimed that steady hydraulic pressure up to 5,000 p.s.i. minimized soil disturbances when obtaining approximately 3 inch diameter samples, by forcing the cutting edges of a sampling head slowly into the soil.

Cutting heads vary with soil conditions, but most workers have recognized the benefits of providing a relief by increasing at least the internal diameter immediately behind the cutting edge (Benz et al 1959, Keefer and Ward 1961, Thames and McReynolds 1961, Palm and Sykes 1962, Boehle et al 1963). Thames and McReynolds (loc.cit.) attributed the benefits of such relief to the reduction of friction between the soil core and the inner surface of the soil retainer ring or collecting tube, and also the lessening of the danger of compaction. There is some apparent flexibility, though, in the desirable amount of relief, as almost all workers have a different recommendation, based on their own experience.

Lutz (1947)	No relief for sampling tubes $2\frac{3}{8}$ inches internal diameter and $1\frac{5}{8}$ inches in length.
Benz et al (1959)	"Core is cut slightly smaller than the inside diameter of the open portion of the sampler" for $\frac{7}{16}$ inch internal diameter tube, 9 inches long.

Keefer and Ward (1961)	"A slight inward taper" caused by the action of conventional pipe cutters in trimming the $1\frac{5}{8}$ inch i.d. tube to 48 inches in length. They also noted that "this taper disappears with use, but is not essential for the satisfactory operation of the sampler".
Thames and McReynolds (1961)	0.01 inch internal relief for a 2.8125 inch internal diameter tube, 3 inches in length.
Palm and Sykes (1962)	An internal relief of $\frac{1}{16}$ inch, and external relief of $\frac{1}{32}$ inch for each of several tubes up to 4 inches internal diameter and 72 inches long.
Boehle et al (1963)	$\frac{1}{2}$ inch relief in internal diameter for a basically 4 inch diameter tube, $34\frac{1}{2}$ inches long.

In the sampler of Thames and McReynolds (1961), the relief commenced $\frac{1}{8}$ inch behind the leading edge. They recommended the use of two types of sampling heads, each of which was interchangeable with the other, and each of which, being 5 inches long, formed the outer casing of the entire sampler, with a 3 inch long soil retainer ring within. The recommended heads were:-

(i) An externally tapered head for use in heavey or moist soil where a conventional sampler with parallel sides would be difficult to extract. The taper allowed the head to be broken loose from the soil with minimum effort and easily removed.

(ii) A parallel sided head which moved into the soil with little friction and which they found useful in dry or compacted soils where extraction was no problem.

Soil retainer rings, similar to those used by Thames and McReynolds (loc.cit.) are common in many samplers designed to extract relatively short "undisturbed" cores. For example, in the "Lutz" Sampler* seamless "tin" cans, $2\frac{3}{8}$ inches internal diameter and $1\frac{5}{8}$ inches high, were used as the soil retainer ring. The upper end of the can was left closed but with an air escape hole, and the open lower end protruded $\frac{3}{8}$ inch below the sampling head so that the can edge formed the leading cutting edge. The filled can was pushed out by a piston arrangement in the cutting head and a fresh can replaced it for the next sample. Samples collected in this manner were, in the main, required for total porosity, volume weight and pore size distribution analysis, but when percolation determinations were required, the "Lutz" Sampler was modified to use stainless steel retainer rings in place of the less rigid and rust prone "tin" cans. Steinbrenner (1950) also used commercial "tin" beer cans, 85 mm. long and with an outside diameter of 70 mm. and a tapered upper shoulder.

Energy supplied to force a sampler into the soil can be in the form of (i) a steady

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*The sampler design by Lutz (1947) has subsequently become known as the "Lutz" Sampler..

pressure, as from a hydraulic jack (Thames and McReynolds 1961, Burnett 1961, Boehle et al 1963) or manual means (Fife 1944, Lutz 1947) or (ii) intermittent force applications ranging from a compressed air driven hammer operating at a maximum of 2,250 blows per minute (Blaney and Taylor 1931), to hand tapping with a wooden mallet (Keefer and Ward 1961).

The state of "undisturbance" of cores formed by "push in" or "hammer" type samplers is not always entirely satisfactory (Northey 1963). He commented that many of these types of samplers could be expected to produce cores with a disturbed outer $\frac{1}{4}$ inch crust. Partially for this reason, he is an advocate of the writing of "undisturbed" in inverted commas, when referring to the state of cores obtained in this manner.

(c) While extensive use of "push in" or "hammer" type non-rotative samplers is made in obtaining relatively short samples, it was noted at an early date by Freckmann and Baumann (1937) that the core was generally somewhat compacted. An alternative approach to the problem of obtaining "undisturbed" cores has been with power or hand driven rotary samplers. These range from units capable of obtaining $3\frac{3}{4}$ inch long cores (van Groenewoud 1960) to test boring equipment where depth of working can run to hundreds of feet (Hvorslev 1949). The features of rotary samplers developed in the period between 1926 and 1960 are tabled on the following page in summarized form:-

TABLE I

The salient features of various rotary soil samplers developed between 1926 and 1960

IDENTIFICATION OF WORKER AND COMMON NAME (IF ANY) OF SAMPLER	NUMBER OF CYLINDERS IN SAMPLER AND DIMENSIONS OF CORE FORMED	MECHANISM TO ENSURE NON-ROTATION OF THE INNER CYLINDER(S)	CUTTING HEAD AND TOOTH DESIGN	RELIEF IN DIAMETER IN CUTTING HEAD.	AUGER FLIGHT(S) DESIGN	DRIVE MECHANISM	FEED-DOWN MECHANISM	TECHNIQUE FOR REMOVAL OF CORE	LIMITATIONS AND DISCUSSIONS
POWELL (1926)	Two coaxial tubes, the inner of which is $6\frac{1}{4}$" internal diameter and 12" long.	Closed upper end of the inner tube takes the thrust against three equally spaced brass rollers ($\frac{3}{16}$" by 1") attached to the inside top of the outer tube.	Three knives fastened removably to the outer tube wall at 20°. Of steel, the knives have inward protruding tips of bronze.	The inner tips of the knives extend "just inside" the leading cutting edge.	No additional auger flights to the three knife teeth.	Removable hand "T" shaft.	Manual pressure from above.	Cutting knives are removed from the outer tube after which the inner tube is extracted from its position within the outer. A plunger rod is inserted in the lower end of the inner tube to remove the core of soil.	Difficulty is experienced in starting the sampling operation making it necessary to remove vegetation from the area to be sampled.
SLATER AND BYERS (1931)	A single toothed steel cylinder which forms a core $4\frac{1}{16}$" diameter and a maximum of 11" long.	Not applicable.	A single auger flight terminates at the lower end in a cutting blade $1\frac{1}{16}$" wide. Additionally, the lower edge of the steel casing has 6 equally spaced teeth cut in it.	Each of the 6 equally spaced cutting teeth on the casing is bent inwards a little to give an inset of $\frac{3}{16}$" on each tooth.	Single flight, representing three complete turns covering a vertical distance of 9". It tapers from $1\frac{1}{16}$" in width at the cutting blade to 1" at the top, and is of $\frac{1}{8}$" moulded strap steel.	Hand "T" shaft rivetted centrally to a top plate of duralium which is itself rivetted to the top of the steel sampling tube.	"T" shaft is threaded for 21" of its length and this thread running in a female thread block and bearing, rigidly fixed to a stand, governs the feed-down rate according to the pitch of the thread and speed of rotation.	In stable soils the sampler is removed and the core is broken away from the bottom of the hole and removed by hand. In less stable soils the core is waxed before breaking away and removal from the hole.	"Cores could readily be obtained in all varieties of soil, except where the presence of pebbles or coarse gravel in the soil impeded the boring process and caused the core to break".
KELLEY et al (1947) "Kelley" Sampler	Three coaxial tubes. An outer drive tube and two inner soil retaining tubes, the extreme inner being split longitudinally. With replacement tubes, the sampler is capable of taking approximately 2", 3" and 4" diameter cores up to 72" long.	Unstated.	A "crow foot" head incorporates a special design to prevent the core from falling out on removal of the tubes. No further specifications given.	"The amount of clearance necessary depends upon the type of soil and moisture content. Sands require less clearance than clays, and wet clays require more than dry clays". Two inner tubes are supplied in each 2", 3" and 4" size. The small have 0.0625" clearance; and the large, 0.187".	The cutting head has a triple start auger flight. There is apparently no flight on the main body of the sampling tube.	Power driven through a combination of chain drive, automotive transmission, Ford differential gears and a 24 h.p. air cooled engine.	The drive arrangement "has the peculiar characteristic of making the downward travel of the tubes co-incidentally responsive to the rotation torque which is variably affected by the toughness of the soil". This automatically selects pressures applied for entry according to the resistance of the horizon the head of the sampler is passing through.	The drive tube is not removed from the soil within a 6' depth but the inner retainer tubes are withdrawn from the drive tube, core removed, and the tubes re-inserted for successive cores. The inside soil tube is split longitudinally for removal of the core.	"Soils that are rocky or contain certain types of hardpan, caliche or other hard materials, such as tree root present a distinct problem and in some cases make it impossible to obtain undisturbed soil cores".
ANDREWS AND BROADFOOT (1958) Modified "San Dimas" Sampler	Three coaxial tubes. An outer cutting tube and within this a sample collector tube which itself houses close fitting soil retainer rings. The core is cut to 2.72" diameter. Although the original sample is $3\frac{3}{4}$" long, the finally trimmed sample in the retainer ring is reduced to 2" in length.	The sample collector tube is attached centrally to the inner of two coaxial hand held "T" shafts. One operator holds this inner handle in a stationary position during the sampling operation.	The sample collector tube forms the leading cutting edge and has an external bevel for $\frac{1}{2}$" which runs into a similar conforming bevel on the outer tube. Two cutting teeth of 60° bevel have their cutting edges extending $\frac{1}{10}$" below the leading edge.	The modified San Dimas sampler has the leading cutting edge of the sample collector tube 0.01" less in diameter than the retaining rings immediately above. This reduced diameter extends for $\frac{3}{4}$" up from the leading edge.	Double start auger flight of 45° pitch.	Hand operated, with two coaxial "T" shafts. One operator holds the sample collector "T" shaft while another operator rotates the outer cutting tube "T" shaft.	Controlled by downward pressure from the operators and the pitch of the cutting teeth.	At the desired depth, the sample collector handle is turned to break off the core. The whole sampler is removed. The outer tube is slid back and the sample collector handle removed. Soil is loosend for $\frac{1}{2}$" around the inside of the collector tube with a knife blade and the retainer rings housing the core are pushed out.	None discussed.
WELLS (1959)	Two coaxial tubes. An inner stationary one, the diameter of which is optionally $1\frac{3}{4}$" or 6", and an outer augered rotating cutting tube of corresponding size to accommodate either inner tube. Thus, two sized cores are possible - $1\frac{3}{4}$" or 6" diameter and up to approximately 36" long.	A ball race thrust bearing assembly transmits the drive to the auger, but ensures that no rotary movement is given to the sampling tube inside it.	A trimming ring at the head of the inner sampling tube forms the leading cutting edge "and the cutters, always slightly above it but cutting snugly to it, remove the surrounding higher material which is then brought to the surface by the auger flights". Tungsten carbide steel tipped cutters are used.	The trimming ring is of slightly smaller diameter than the main body of the inner sampling tube. For the $1\frac{3}{4}$" sampler tube the difference is 0.35", and for the 6" tube a difference of 0.25" is allowed.	No detailed description is given except that extension auger flight lengths are available for sampling at greater depths than 36".	Two commercially available borers are used. A heavy duty machine and a standard machine, both operating from the power-take-off of the transporting Land-Rover vehicle.	With the heavy duty borer this is by a hydraulic winch. In the case of the standard borer machine, a mechanical winch is used.	An ejector plunger arrangement is used to push the core (whether $1\frac{3}{4}$" diameter or 6") out of the inner tube after the latter has been removed from the outer rotative casing.	"Layers which are too hard either from dryness or stoniness, for the trimming ring to penetrate will make sampling either prolonged or impossibl However, the weight and vibration of the equipment is often sufficient to make the sampler penetrate quite hard materials.
van GROENEWOUD (1960)	A single tube forming a core $2\frac{7}{8}$" diameter and up to $3\frac{3}{4}$" long.	Not applicable.	No teeth. A smooth bevelled edge is formed on the sampling tube.	The cutting edge is spun inwards and machined to give a diameter $\frac{2}{32}$" less than that of the body of the tube. This extends for $\frac{3}{16}$" up the tube.	None present.	Hand "T" shaft with a slotted lower end, fitting over a $\frac{1}{4}$" rod passing transversely through the upper portion of the cylinder. The operator stands on the base plate.	The top of the cylinder has a $\frac{1}{4}$" rod transversely through it. The outer projecting ends of the rod follow the threads in a threaded boss brazed to a base plate that is positioned on the level soil from which the sample is to be taken.	When the cylinder is screwed right through the base plate the latter is lifted off, and the cylinder is dug out with its retained core. A plunger is then used to push the core out of the cylinder.	Stones are an interference but roots up to $\frac{5}{16}$" diameter were no trouble, thus giving this machine an advantage over those with cutting teet which tend to tear at the roots with consequent disruption of the core bein formed within.

A comparatively recent coaxial tube sampler has been developed in the Soviet Union by Starodumov (1962) and is worthy of a special description because of its unique design.

It consists of four coaxial cylinders. The inner most tube is merely a cartridge or liner that is removed after the boring operation, and is opened to expose and remove the core. The next tube out, viz. the stationary inner sleeve, as well as housing the removable liner, also forms the guiding axis about which the moving auger cylinder revolves. The third tube out from the centre is the outer rotating cylinder with auger flights and soil cutting teeth which form a continuous screw from the cutting tip to the top. External again to this is a stationary outer tubular casing equiped with vertical stabilizer wings on the lower end to discourage rotation, and a system of large holes throughout its length through which the soil that is brought up by the rotating auger within, passes to the outside. The augered cylinder rests on two sealed ball bearings, while the stationary tubes form an integral part of the casing of the entire sampler and driving motor. A cutting ring, housing a replacable ring borer is fastened to the lower part of the sleeve. Several ring borers are supplied with the drill set.

The auger tube assembly is driven by a 3 h.p. gasoline motor provided with a centrifugal clutch and reduction gears giving the auger a normal rotation speed of 196 r.p.m. As the soil cutter rotates, it drills the soil along the ring surface, leaving the core inside. The cutting ring is driven into the soil by the weight of the borer.

To remove the soil sample from the borer, the cutter is removed from the auger tube by twist release from its bayonet fitting. The cutting ring is then removed and the core taken out in the liner from the stationary sleeve, together with the ring borer. To take a new sample the empty ring borer and liner are inserted in the drill. The cutting ring is screwed on, cutter repositioned in its bayonet fitting, and the core drill is ready for operation.

There is no mention of external or internal diameter relief in this sampler, but the core obtained is reported to measure 7 cms. diameter, and up to 95 cms. long. Much shorter samples can be taken, in which case the inner liner to the stationary sleeve is dispensed with, the sample being retained in the removable ring borer. When taking samples, depth of working is conveniently observed by the use of cm. graduations on the outer casing.

Stace and Palm (1962) and Palm and Sykes (1962) overcame the difficulty caused by undesirable frictional and adhesive conditions existing between sample collector tubes or retainer rings and certain soil types and moisture contents. To this effect, with their "hammer in" type sampler, they stated that before use, the tube must be coated inside with a thin film of mould oil. In Australia, the product "Shell G.B. 800" was satisfactory. This oiling was essential to prevent the core from jamming in the tube. However, it was stressed that only a thin film was necessary and no contamination of the sample occurred. In practice, the outside of the tube was also coated with the oil, although this was omitted if desired. They went further to comment that silicone, both as an emulsion and pure, had also been tried as a lubricant but proved no better than the mould oil. According to these workers, a tube coated on the outside with "Teflon"* had been used by Greacen** to sample loamy surface horizons. Greacen pointed out that this tube was extremely easy to extract from the soil, but the lack of durability of the coating, due to the abrasive action of the sand grains, and the cost of the treatment, prohibited its use for large scale routine sampling. Commenting on this, Stace and Palm (loc.cit.) noted that a "Teflon" coated tube might, however, be helpful in sampling heavy wet clays.

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* "Teflon" is the trade name of E.I. du Pont de Nemours and Co., for tetrafluoroethylene.

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II THE TRANSPORTATION, STORAGE, AND PREPARATION OF SOIL SAMPLES PRIOR TO LABORATORY INVESTIGATIONS OF HYDRAULIC CHARACTERISTICS

There appear to be two general approaches to the problem of encasement of cores for transportation and treatment; (a) placing the core in a rigid container, or (b) applying an intimate coating of liquid encasement that sets hard in a relatively short time. Several workers have mentioned their experience with, or thoughts on, portable rigid containers for core encasement (Kelley et al, 1947; Lutz, 1947; Marsh and Swarner, 1948; Steinbrenner, 1950; Taylor and Heuser, 1953; Wells, 1959). Kelley et al (loc.cit.), on the development of the "Kelley" sampler, commented that the technique of transporting the undisturbed cores had not been studied in detail. It was thought, however, that tubes split lengthwise, to replace the split tubes of the sampler machine, could be used satisfactorily. Until making that statement, Kelley and his associates (loc.cit.) had used rolled sheet metal containers for transporting cores to the laboratory. Marsh and Swarner (1948) continued with the original recommendation of Kelley et al (1947) and wrapped their 4 inch by 36 inch cores taken with the "Kelley" sampler in pre-rolled sheet aluminium casings made of 0.020 inch 3S half hard aluminium. They secured the casings with wire and transported them to the laboratory on a pickup truck bedded with straw. In the laboratory, the cores had about 1 inch of soil removed from the lower end, and the space left was packed with pea gravel. A wooden base was secured on this end and was centre drilled to take a stopper. That portion of the wood exposed to water was impregnated with paraffin wax. With the wooden base in place, the drilled hole was partially filled with gravel and glass wood, and a stopper with a glass drain tube inserted. The whole core was then placed upright in a wooden rack for permeability trials. To study pressure distribution in the profile, the aluminium casing was drilled at points corresponding to horizon boundaries, the drill hole continuing for about 1 inch into the soil core. Short glass tubes, with a 1 inch square thin wooden collar, were inserted and wired to the core, with a rubber band forming the seal between the collar and the core casing. Manometers were then connected to these short tubes by rubber extensions.

These workers commented that the aluminium casings proved inexpensive, easily handled, and practical containers for transportation, but that certain disadvantages were apparent with their use in the laboratory. At the point of overlap, a small vertical channel was formed, down which water may flow. Also thin walls would not support threaded connections making it necessary for manometer connections to be externally supported. The lack of transparency was considered also to be inconvenient. On this subject, they noted that the

U.S. Bureau of Reclamation had at that time engaged a commercial plastic manufacturer to develop a transparent plastic container which, it was hoped, would obviate all the disadvantages of the aluminium wrappings.

Taylor and Heuser (1953) carried this idea of utilizing plastic containers still further, and combining with the thoughts of Kelley et al (1947), they placed samples from the "Kelley" sampler in split plastic tubes. When the tube was clamped, the core was sufficiently tight in the tube so that it would not slip, but undue compression was avoided. It was found necessary to apply melted paraffin wax to the tube at the surface of the soil to prevent water from channelling between the soil and the plastic. Parr and Bertrand (1960) considered this method to be among the best that had been used in the handling of soil cores.

Wells (1959) made little reference to transportability problems except by commenting on a modified use of his sampling equipment, which jacked galvanized iron cylinders into sandy soils so that the sample could be easily and accurately collected without contamination, and transported to the laboratory and inspected, analysed, or stored.

Among the first workers to consider the use of temporarily liquid encasements for cores were Slater and Byers (1931). In their technique, the core was encased in paraffin wax in the field using a cylindrical "tin" container, 4 inches diameter and $9\frac{1}{2}$ inches high, with a threaded metal cover for each end. The tin was placed over the core and filled with molten paraffin. When the paraffin had set solid, that portion of the 11 inch core protruding beyond the end of the casing was cut off flush, and the remaining cover screwed on prior to transportation to the laboratory. On arrival in the laboratory, the end of the core cut flush with the casing was further smoothed with a special knife tool to leave the surface $1\frac{1}{2}$ inches below the casing rim. The cover was unscrewed from the lower end of the container and a base, which resembled a funnel-shaped cap with an outlet, substituted. This cap held in place a perforated brass plate screen on which the core itself was supported. Following this preparation, the cores and containers were placed on a wooden bench support in batteries of six. Holes were drilled in the bench through which the leachate dripped, to be caught in beakers beneath.

Slater and Byers (loc.cit.) noted some inherent difficulties in the waxing technique. When the cores were dry and the weather warm, paraffin of low melting point, and hot, penetrated the cores to a considerable extent. Conversely, when a core was moist and relatively cold and the temperature of the wax applied was proportionately too low, noticeable leaks developed between the paraffin sheath and the core. They added that, for several minor reasons, they had found that a paraffin melting at 45°C was best in cool weather, and one with a melting point of 55°C best in hot or warm conditions.

Paraffin was was used by Bloodworth and Cowley (1951) for entire sealing of cores from the "Kelley" sampler to prevent loss of water during storage. They noted that the paraffin coating added to the strength of cores and reduced the care required in handling them. Applied with a 1 inch or 2 inch paint brush at 100 - 120°C, or by dipping shorter (3 inch - 6 inch) cores in it, they stressed that each coat be allowed to harden before applying the next. They also stressed that cores must be treated within 24 hours after cutting to prevent shrinkage due to drying along the outside edges, and that storage in the sealed state must be in a cool place as the paraffin became soft and stuck to the bottom of the containers if the temperature was too high.

In the laboratory, the end portions of the seal were removed and two 20 guage galvanized iron sleeves were clamped around each end of the sample. Both sleeves were placed to protrude beyond the extremities of the core and were tightened in place with wing bolts. The upper sleeve measured 5 inches by 15 inches when flat, while the lower one was $2\frac{1}{4}$ inches by 15 inches, both being rolled to a 4 inch diameter to fit the core. Sealing to prevent water movement between the core and upper sleeve was accomplished by pouring a small amount of hot paraffin into the join. A screen of bronze, fixed to a brass ring, was rigidly attached within the lower sleeve to support the core, and a small funnel in a stand acted as a base for the sleeve and core in the position for permeability trials. The funnel spout was directed into a measuring cylinder for recording purposes.

Reeve and Luthin (1957) commented that a very satisfactory technique for encasing larger cores was to seal the core into a plastic cylinder of diameter larger than the core, with a water-bentonite slurry. They claimed that the slurry conformed to the configuration of the core and was essentially impermeable to the flow of water.

III SUPPLEMENTARY LABORATORY EQUIPMENT ASSOCIATED WITH HYDRAULIC STUDIES OF "UNDISTURBED" SOIL SAMPLES

Concerning the application of water to the core surface for permeability trials, Fireman (1944) stated that there were three principal types of constant water level controls: an overflow system, a Mariotte or inverted flask, and a float valve. "The overflow system requires a minimum of equipment and attention, but it also requires a large, easily available water supply," he claimed. "The Mariotte flask does not require excess water but unintentional disturbance of the soil is almost unavoidable, and difficulties are encountered in recharging the reservoir." He preferred the float valve principle, and recommended his own variation of it. This was constructed simply and cheaply from an adapted glass light bulb and an automobile or bicycle inner tube valve stem. With this arrangement, one float valve could, he claimed, serve as many as 24 soil permeameters simultaneously.

Bloodworth and Cowley (1951) briefly explained the action of the inverted flask. A vertical glass tube from a stopper in the neck of the flask had a flared end terminating just above the soil surface. As water penetrated the soil, the closed system was broken at the flared end of the tube, allowing air to rise into the flask and hence water to flow down and out of the tube, until the water level on the core rose sufficiently to cut off the air supply again. However, when these workers were analysing a battery of 8 permeameters, they employed a constant head overflow reservoir with a common supply line which took water under a constant pressure to 8 branch lines, each leading to a sample. In this way, a constant head of any desired magnitude was maintained on each of the samples.

A variation of the inverted flask devised by Steinbrenner (1950) incorporated inverted 500 ml. volumetric flasks, with the mouths reaching down almost to the bottom of carbon funnels inserted in stoppers in the top of the beer cans encasing the samples. Prior to the trials, the presaturated samples had distilled water added until the cans were full and the water level in the carbon funnels rose to the mouths of the inverted flasks. Thereafter, the operation of the system was essentially the same as that of Bloodworth and Cowley (1951).

In regard to the constant head maintained on samples, Taylor and Heuser (1953) recommended adjusting their feeding system to keep 1 - 2 cm. of water on the surface, and to calibrate the system to indicate the volume of water used. Slater and Byers (1931), who also recommended a 2 cm. head, arranged their system so that distilled water was fed in through a Mariotte bottle constant-level device, supported along the back of the bench. The bottle supplied a horizontal feed pipe located 2 inches below the tops of a battery of 6 cores in containers, the core tops being themselves $1\frac{1}{2}$ inches below the container rims. Connections of glass and rubber tubing supplied the 6 cores, each tube combination being in the form of an inverted U, thus acting as siphons and drawing water over the tops of the containers to supply the cores.

The principle of the Mariotte bottle was employed by Bower and Petersen (1950) to maintain a constant water level at the top of permeameter cans, consisting of modified and extended "Lutz" sampling cans housing "undisturbed" cores. Transparent plastic tubing was considered a suitable material of which to construct the manifold, as entrapped air was readily visible. They recommended that the minimum internal diameter of the tubing to supply batteries of 10 units be $\frac{1}{4}$ inch, to keep the frictional head loss at a minimum.

An interesting alternative approach to any of the previously listed devices, was in applying water to the top of cores from a burette to a level indicated by a sharpened nail (Marsh and Swarner 1948). This was used in studying intermittent water applications, and a pad of burlap was used on the surface to dissipate the energy of the impact of the supply water. At frequent intervals, the water would be replenished and the time rate of disappearance thus obtained.

IV THE LABORATORY STUDY OF WATER FLOW THROUGH "SATURATED" SOIL

The infiltration rate of a soil has been described by Richards (1952) as the maximum rate at which a soil, in a given condition at a given time, can absorb rain. Parr and Bertrand (1960) felt that it could also be defined as the maximum rate at which a soil will absorb water impounded on the surface at a shallow depth when adequate precautions are taken regarding border or fringe effects. They stated that, quantitatively, infiltration rate is defined as the volume of water passing into the soil per unit of area per unit of time. It has the dimensions of velocity , $(\frac{L}{T})$.

Permeability, they defined qualitatively as being the quality or state of a porous medium relating to the readiness with which such a medium conducts or transmits fluids. From a report of a Committee of the Soil Science Society of America, the Chairman (Richards loc. cit.) stated that "the qualitative meaning needs no change. However, when an attempt is made to be quantitative and to express permeability with numbers, considerable variability in usage occurs". For general clarification, this Committee recommended that definitions of permeability, such as that given above, refer to intrinsic permeability (designated by 'k'') and that if it is an author's preference to use the term permeability in connection with the quantitative Darcy equation,

$$v = ki$$

(in which 'v' is the macroscopic flow velocity, and 'i' the hydraulic gradient), that it be made clear in the writing, at least once, that hydraulic conductivity is the implied quantity*. Permeability, or 'k', according to Swartzendruber (1962) can itself be identified in terms of 'k'', or intrinsic permeability by the expression

$$k = \frac{k'\rho g}{n}$$

where 'n' is the fluid viscosity, 'ρ' the fluid density (water density if 'i' is in terms of water column), and 'g' the acceleration of gravity.

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* It is the author's intention to use the term permeability as being strictly synonymous with hydraulic conductivity, or the Darcy 'k'. Expressed in inches per hour, it has the dimensions of velocity $(\frac{L}{T})$ and is determined by direct measurement of the volume of water flowing through a body of soil in a given time under a given hydraulic gradient. The term intrinsic permeability, 'k'', (having the dimension of length squared, L^2), will be used when referring to the quality of a porous medium relating to its ability to transmit fluids.

A further definition by Parr and Bertrand (1960) was that of the term of percolation. This, they stated, is a quantitative term applying to the <u>downward</u> movement of water through soil - especially the downward flow of water in saturated, or nearly saturated, soil. For a given fluid, the determination of the permeability of the medium depends upon a knowledge of the hydraulic head distribution, the boundary conditions and the macroscopic flow velocity. In the laboratory, simplified boundary conditions are used for convenience in making this determination. Reeve and Luthin (1957) noted that usually rectilinear flow is impressed upon a sample of the porous medium by encasing it with an impermeable wall of some simple geometrical shape, such as a cylinder or parallelepiped. Furthermore, control is exercised over the hydraulic head distribution with both inflow and outflow surfaces, and provision is made for measuring the macroscopic flow velocity, $\frac{Q}{A}$, either upon entry or exit from the sample. For such conditions, they wrote the Darcy equation as

$$Q = kA \frac{H_1 - H_2}{L}$$

where 'Q' is the volume of water discharged per unit time, 'H_1' is the hydraulic head at the inflow end, and 'H_2' the hydraulic head at the outflow end, 'k' is the hydraulic conductivity, 'L' is the flow length, and 'A' is the cross-sectional area. Earlier, Slater (1948) had used 'h' as a simplified expression of '$H_1 - H_2$'. On the question of head, Schiff (1953), working with ring infiltrometers and ponds, identified surface head as the head of water on the surface of the soil, and hydraulic head at any point in the profile as the head of water whose boundaries stretch from the surface of the water overlying the soil to the depth in the soil of the particular point in question. Thus, hydraulic head includes in its dimensions the surface head.

Slater and Byers (1931) came to the conclusion that it was advisable to keep the value of 'h', $(H_1 - H_2)$, in a vertical core approximately equal to the length of the core, 'L', as this enabled the expression $\frac{L}{h}$ to be eliminated from their flow rate equation

$$R = \frac{VL}{ATH}$$

where 'R' is the flow rate, 'V' the volume of water percolated, 'A' the surface area of the core, and 'T' the time. Another reason for eliminating $\frac{L}{h}$ was that in some soils a decided increase in the surface head did not materially affect the percolation rates (Slater and Byers loc.cit., Fireman 1944, Swartzendruber 1962). It is interesting to note here that Bower and Petersen (1950) adjusted the surface head on their permeameters to be exactly half of the hydraulic head, 'h'. In this condition, the hydraulic gradient, $\frac{h}{L}$ in the Darcy equation, became 2, thus simplifying subsequent calculations. Commenting on saturated gravitational downward flow in cores in comparison with an idealized system, Slater (1948) noted that 'h' was considered equal to 'L' by Darcy's law, and that velocity remained constant for any length of soil column. This concept was not in agreement with the concept of terminal velocity in his own idealized system, but he further noted that Darcy's law was empirical in origin and had practical rather than absolute accuracy.

Commenting on Darcy's law, Swartzendruber (1962) noted that Darcy himself recognized that his relationship was not valid for high fluid velocities. Swartzendruber (loc.cit.) went further to state that it seemed well established that when the hydraulic gradient exceeded a critical value, the flow velocity was no longer proportional to the hydraulic gradient, but increased less rapidly than the gradient. This, he said, could be accounted for by saying that, since viscous forces no longer masked the inertia and turbulance forces, not all the driving force of the hydraulic gradient was used to overcome viscous resistance.

Miller and Low (1963) established the presence of a threshold gradient for water flow in clays. This threshold gradient, they claimed, was the hydraulic gradient below which no flow occurred. Such a threshold gradient apparently decreased with decreasing clay concentration and increasing temperature. At gradients above the threshold gradient, the flow rate - gradient relationship was essentially linear, except at low gradients, for the concentrated clay systems, but curvilinear for the less concentrated clay systems. These results were explained on the basis of a quasi-crystalline water structure which developed in the clay-water systems as a result of water-surface interaction.

Many investigators measured rates of percolation as the volume of leachate emerging in a given time, (Slater and Byers 1931, Fireman 1944, Bower and Petersen 1950, McCalla 1950, Steinbrenner 1950, Bloodworth and Cowley 1951). Other workers, however, preferred to measure the water usage rate and endeavoured to record the volume of water infiltrating in a given time, (Marsh and Swarner 1948, Bloodworth and Cowley 1951, Taylor and Heuser 1953, Miller and Gardner 1962). Schiff and Dreibelbis (1949) combined the advantages of both, taking simultaneous readings of inflow (from a burette) and outflow (into a measuring cylinder). When the volume of leachate equalled the volume applied, in a given time, either volume was then used to compute the true saturated percolation rate.

In a laboratory investigation carried out by Miller and Gardner (1962) of the effects of textural and structural stratifications within the profile on the rate of water infiltration into soil, a unique infiltration recording device was utilized. The device obtained rates of infiltration by measuring the time required for an air bubble to pass through a known volume of a calibrated small-bore glass tube as water flowed through the tube to the soils. Electrodes with a small D.C. voltage between adjacent pairs recorded, on an electronic potential strip chart recorder, voltage changes as an air bubble passed between pairs. Knowledge of the volume of the glass tube between any two pairs of electrodes furnished sufficient data for computation of the flow rate in volume units per unit time.

According to Marshall (1959), there has been a variety of permeability units used by various workers. Two tables of the ranges of values are given below, neither of which has allowed for the effects of cracks.

Class	Hydraulic Conductivity 'k' (inches/hr.)	Comments
Extremely slow	Less than 0.001	So nearly impervious that leaching process is insignificant.
Very slow	0.001 - 0.01	Poor drainage results in staining; too slow for artificial drainage.
Slow	0.01 - 0.1	Too slow for favourable air - water relations and for deep root development.
Moderate	0.1 - 1.0	Adequate permeability.
Rapid	1 - 10	Excellent water holding relations as well as excellent permeability.
Very rapid	In excess of 10	Associated with poor water holding conditions.

TABLE II

Permeability classes of Smith and Browning (1946) for saturated subsoils

Class	Hydraulic conductivity, 'k'		Intrinsic permeability, 'k′'
	10^{-5} cms/sec.	inches/hr.	10^{-10} $cm.^2$
Very slow	less than 3	less than 0.05	less than 3
Slow	3 - 15	0.05 - 0.2	3 - 15
Moderately slow	15 - 60	0.2 - 0.8	15 - 60
Moderate	60 - 170	0.8 - 2.5	60 - 170
Moderately rapid	170 - 350	2.5 - 5.0	170 - 350
Rapid	350 - 700	5.0 - 10.0	350 - 700
Very rapid	in excess of 700	in excess of 10.0	in excess of 700

TABLE III

Permeability classes of O'Neal (1952) for saturated subsoils and the corresponding range of hydraulic conductivity and of intrinsic permeability

V SOIL AND FLUID PROPERTIES RESPONSIBLE FOR VARIATIONS IN INTRINSIC PERMEABILITY

Reeve and Luthin (1957) listed the factors affecting permeability as:-

(a) Interaction of the Fluid with the Porous Medium

They classed porous media as either stable or unstable, depending on whether or not there was a change in the size or arrangement of pores as a result of passage of fluid through the medium. They also commented that, due primarily to the adsorption of water within the expanding type lattice of montmorillinitic clay particles, soils containing montmorillinitic type clays undergo a much greater physical change upon wetting and drying than soils of other type clay minerals. The effect of various exchangeable cations on the change in permeability as a result of wetting with water was investigated by Reeve et al (1954) and Brooks et al (1956) . They illustrated, independently, that exchangeable sodium was particularly effective in causing dispersion, swelling, and structural breakdown of soils. Because of these known interactions, the question of what solutes to include in water that is being passed through soil during a permeability measurement is a difficult one (Marshall 1959). For irrigation investigations, Marshall (loc.cit.) quoted Fireman (1944) as recommending the use of water which would be applied in practice to the land. This was also the view of Marsh and Swarner (1948). Fireman (1944) also generalized that "because of its effect on soil dispersion, the lower the salt concentration, the lower the soil permeability".

Presumably to simulate the chemical composition of rainfall, other workers recommended the use of distilled water as the infiltrating fluid (Slater and Byers 1931, Steinbrenner 1950). A further unrelated group of workers made no recommendations at all and thus appeared satisfied with the use of tap water (Schiff and Driebelbis 1949, Bloodworth and Cowley 1951, Taylor and Heuser 1953, Miller and Gardner 1962).

(b) Blocking of Pores

This condition, Reeve and Luthin (1957) stated, occurs where the test fluid is a liquid and pores are blocked by a gas that is entrapped, or where the test fluid is a gas and the pores are blocked by a liquid contained within the porous medium. The problem of confined air has been discussed by a number of investigators, two of which (Slater and Byers 1931, and Fireman 1944) advocated presaturation of the cores from the bottom to facilitate upward displacement of air. Fireman (loc.cit.), however, commented that this required relatively complicated and expensive equipment, and on investigating the merits of upward and downward displacement, he later found that no more air was trapped in soil pores by downward flow than by upward flow. He also found with disturbed samples that the permeability values obtained by the use of both types of flow were different in the early stages of flow, but later were in excellent agreement. Steinbrenner (1950) claimed that by saturating his cores slowly over a period of 12 hours, entrapment of air was prevented.

Christiansen et al (1946) were able to cause maximum hydraulic conductivity to occur at the beginning of flow by pre-displacing the air in the porous medium with more readily soluble CO_2. They obtained similar results by vacuum wetting, which ensured that little air was present to be trapped. Conversely, however, Wycokoff and Botset (1936) and Childs and Collis-George (1950) found that flowing water containing dissolved gas could release a portion of this gas to accumulate in the porous medium and hence to reduce the hydraulic conductivity. The latter workers found no conductivity decrease using boiled distilled water. Gupta and Swartzendruber (1964) restated that large decreases in conductivity could be more reasonably related to bacterial activity than to air entrapment. Their work indicated that air was being continually removed, rather than being accumulated by the release of dissolved air from the flowing water.

(c) Microorganisms

Allison (1947) was the first to show conclusively the magnitude of the effect that microbes and their decomposition products had on permeability rates. Commenting on his generalized curve of permeability as a function of time (Fig. I), Allison (loc.cit.) stated that the overall decline in phase 3 was attributable to biological clogging of pores with microbiol cells and their synthesised products, and/or physical disintegration of aggregates under prolonged submergence. The initial decline in phase 1 he attributed to dispersion and swelling of soil particles (as outlined previously), while phase 2 was considered a result of the gradual solution of entrapped air (also commented on above). These findings are in general agreement with the work of McCalla (1950).

On the overall decline in percolation, Slater and Byers (1931) stated that "usually there occurred a decrease in rate with long continued percolation, regardless of the moisture content of the core at the time taken or of the apparent duration of such content in the field". In contrast to the explanation of Allison (1947) of the decline in phase 3, Bodman (1938) attributed the overall decline solely to a consequent dispersion and rearrangement of particles. Marshall (1959) quoted Greacen and Huon (1953) as doubting the explanation of Allison (1947) . They apparently also found a decline in phase 3 in their trials with beds of aggregates where the entire runs occupied only a few hours, too short a time for microbiological activity to cause blocking of pores.

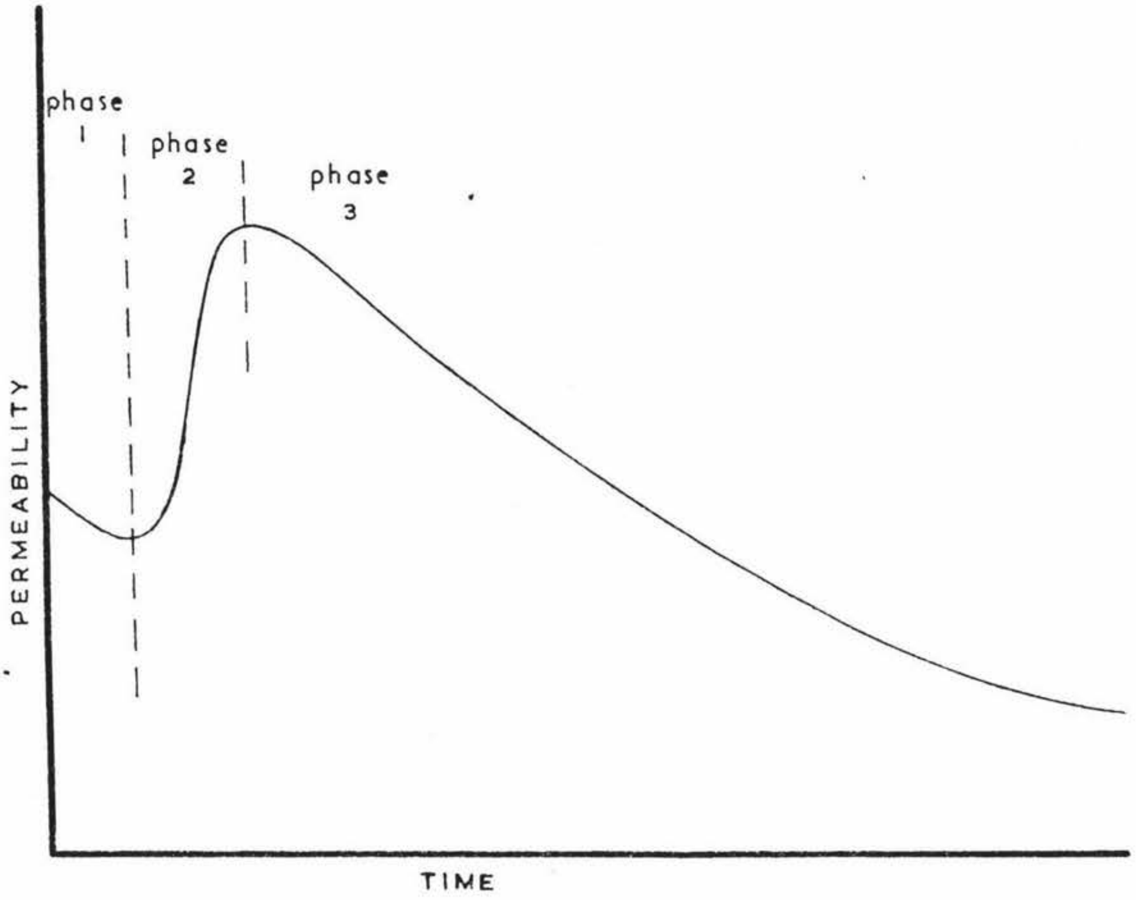

FIGURE I

The generalized permeability - time curve of Allison (1947)

(d) Nonhomogeneity of Porous Materials

This, according to Reeve and Luthin (1957), involves a statistical problem of sampling as the number of samples required for soil appraisal is increased if the soil is highly variable or if the samples are small in size.

(e) Soil Anisotropy

Because of the sedimentation process itself, many soils and aquifer materials are anisotropic. Thus the horizontal permeability of a homogeneous sand or gravel may be appreciably greater than its vertical permeability. The reverse situation was also possible.

Additional to the list of Reeve and Luthin (loc.cit.) of variable permeability factors, Fireman (1944) and Miller and Gardner (1962) considered variations in temperature to be an important factor. The last named considered it to be important enough to carry out their infiltration rate measurements in a temperature-controlled room at 25 ± 5°C.

The wide variation of percolation rates between soil cores, even for the same soil type, has been mentioned by numerous investigators (Slater and Byers 1931, Marsh and Swarner 1948, Schiff and Dreibelbis 1949). Schiff and Dreibelbis (loc.cit.) claimed that in spite of precautions to eliminate the sample having cracks or leaks, considerable replication was necessary to obtain representative values. Variations between samples, they put down to being due to a number of factors, the most important of which were:

(i) soil heterogeneity
(ii) influence of plant roots and residues
(iii) worm-holes and other biological channels
(iv) particle size and parent material fragments
(v) pore size and its continuity
(vi) stability of soil structure
(vii) entrapped air.

Slater and Byers(1931) reported additional causes of variation. They felt that passageways formed by cracks and fissures and the decay of roots caused a variance in flow; in some cases, ant-holes and worm-holes made it necessary to discard the core completely. Cores were also rejected if, after the experiment was completed, the section of the core revealed obvious mechanical defects. During the running of percolation trials, data were discarded if the leachate showed an unusual amount of sediment or cloudiness, and if there had been abrupt and irregular changes in percolation rates.

Schiff and Dreibelbis (1949), in addition to listing factors causing variations between samples, claimed that some methods in use did not seem to simulate natural conditions, because cores were frequently saturated for some time prior to the determination of percolation rates, and heads were maintained. Even the manner of saturating cores, they said, was different from that which occurs in nature.

VI METHODS OF INDIRECT ASSESSMENT OF INTRINSIC PERMEABILITY

Indirect assessments of intrinsic permeability have been undertaken by adopting different approaches. Baver (1939), Roe and Park (1944) and Smith et al (1944) proposed methods for estimating intrinsic permeability by measurement of the pore size distribution with moisture tension methods. Aronovici (1946) commented that these methods probably had merit when applied to the specific problem for which they were developed, but that study of them revealed that they required a too-exacting laboratory technique, constant temperature facilities, and were not adapted to all types of soil materials. Rather, Aronovici (loc. cit.) advocated the procedure of mechanical analysis. He claimed that his procedure satisfied several basic requirements essential to extensive field application. These requirements were: handling a large number of samples in order to obtain accurate representation of highly stratified materials; adapted to use of disturbed samples taken at considerable depth and frequently below the water table; and simple technique and equipment. The proposed indirect measure of permeability was applied specifically to the water flow under gravitational head differentials where all noncapillary cores and usually capillary cores were filled with water. He felt that pore size distribution in part was a product of grain size distribution or texture, and that pore size, rather than total porosity, determined the intrinsic permeability of that material. He noted, however, that sediments containing considerable clay commonly possessed structural features which affected pore size more strongly than the grain size. He thus concluded that estimates using mechanical analysis alone must be confined to sediments having a rather low clay content. Since then, several investigators have studied mechanical analysis as a technique to estimating intrinsic permeability.

A more direct, though somewhat subjective method of estimating the percentage of different sized particles, is the assessment of soil texture by feel. It is well known that, with a little practice, it is possible to asses the textural class of a soil - whether it is a loam, silt loam or clay for example - by feel. Any sand present will contribute a raspy feel, silt a silky feel, and clay a very smooth and sticky feel. Clay will also "take a polish". The feel of a particular soil will depend on the porportion of these components present. The determination, although qualitative, has the advantage that it is quick and may be made at any time and in any circumstance in the field. Clarke (1957) noted that the total area of the surface of the soil particles increased rapidly as the particle size diminished, and this increase in surface area had a considerable effect upon cohesion in the soil mass. Another property of the soil mass which he considered was influenced by texture, as well as by structure and constitution, was the magnitude of the interpaticle space. Thus, Clarke (loc.cit.) concluded that texture, including the amount of ultra-fine or colloidal material possessing a high degree of hydration, determined the water relationship of the soil.

Complementary to textural determinations, certain practical field assessments of natural permeability were discussed by Hudson et al (1962). Commenting on the resistance to penetration of a conventional spade, they wrote that where permeability was naturally good, the subsoil was sufficiently soft to be dug with a spade, even under the driest conditions. Although drawing to the reader's notice a notable exception, they claimed that a subsoil which was hard when dry, indicating a high clay content, was usually associated with soils liable to wetness and a softer subsoil, with a free draining profile. It was in the colours of the subsoils, however, that the most reliable indications existed of the extent to which land may be wet. Hudson and his associates (loc.cit.) felt that soils having good natural drainage were characterized by uniform colours in each horizon, although horizons themselves may vary in intensity of coloration. The colours of the subsoils were usually reddish-brown or yellowish. They pointed out that soils with bad natural drainage had subsoils typified by grey, blue, or greenish colours which were, as a rule, mottled with brown or yellow and yellowish-brown patches. O'Neal (1949) presented evidence that indicated that such factors as mottling and texture alone could be poor guides to intrinsic permeability. He found that, in some cases, heavy textures went along with slow permeability, and light textures with rapid permeability, but that, in the main, texture alone was not a reliable clue. Nor, he felt, was mottling, unless the reason for it was known. A soil may be mottled, regardless of its permeability, if the water was held by a barrier or was the result of seepage or a perched water table. In general, it would seem that structure was the most significant factor in evaluating intrinsic permeability, although he stressed that it could not be correctly evaluated on the basis of type of structure alone. More important was the relationship between the length of the horizontal and the vertical axes of structural aggregates, and also the direction and amount of overlap of aggregates. In some soils, the durability of aggregates seemed to be correlated with intrinsic permeability, while in others it was the size and number of visible pores or the direction of easiest natural fracture. He did stress, however, that usually all the factors mentioned in his work must be considered singularly and in relation with one another, adding that intrinsic permeability could not be evaluated on the basis of one characteristic alone.

SECTION C

SOIL AND SITE CHARACTERISTICS AND THEIR ASSOCIATED PROBLEMS

A recent alluvial soil which past experience has shown to exhibit a special drainage problem, was that located at Ongley Park, a sports ground under the administration of the Palmerston North City Council. Past application of conventional methods of drainage investigation and rectification has failed to have any appreciable beneficial effect. From profile maps of the Manawatu District, the area concerned was considered to have a fairly typical profile for those alluvial soils of the District exhibiting this particular drainage problem. Indeed, such a problem appeared to be fairly wide-spread on alluvial soils bordering the banks of the Manawatu River.

This situation seemed to present a case where a more fundamental study of hydraulic characteristics of the profile could contribute towards a better understanding of the drainage problem. This type of approach demanded examination of "undisturbed" columns of soil in the laboratory.

I The Problem

In brief, the poor drainage condition was largely a winter problem. During the wet season, water lodged on the surface, and with the action of stock (or sporting footwear) the surface crust became distinctly pugged and muddy. The possibility that surface lodging was, in fact, a direct result of surface sealing by pugging action on the dampened soil, was not overlooked. However, evidence tended to point to another cause - or at least a joint cause. For one, the pugging was by no means uniform - even over an area such as Ongley Park. Those fields that became extensively pugged through concentrated playing did not necessarily show a greater accentuation of the common drainage problem than did those where play was less frequent, or those of other areas in the surrounding, intensively stocked farm land. Additionally, examination of the profile by Bowler (pers. comm.) in 1950 under very damp conditions revealed that the top 12 inches appeared to be extremely moist and probably close to saturation, while the profile from 12 inches down to 36 inches appeared comparatively dry (probably about field capacity). The profile pits from which these observations were made were excavated about midway through a particularly wet season (average monthly rainfall of 4.8 inches over the winter period of June, July and August), ample time for a wetting front to move down into a soil as far as it was allowed to by any restrictions within that profile. Under such conditions, many Lawsoniana trees in the area had thrived for a number of years. This tree species was known to be intolerant of a perpetually wet subsoil for even short periods of time, so that for their survival, it appeared that a free draining subsoil was essential.

The above observations suggested that the problem was not predominantly one of low subsoil intrinsic permeability, and assessment of indirect physical soil properties tended to lend weight to this suggestion. Initial subjective analysis of texture by feel at each of four randomly selected points on Ongley Park revealed that below 18 - 24 inches in the profile, the textural class was anything from a silty loam to a sandy loam. From evidence presented by O'Neal (1949) and Clarke (1957), one would not have expected textural classes, between and including those named, to show extreme impedence to water flow, At the worst, unless in a high state of compaction, such a subsoil would be expected to deal adequately with normal Palmerston North winter rainfall (which has averaged 3·54 inches a month for the months of June, July and August over the last 15 years). That this deduction was at least not disproven was seen when studying Manawaroa and Ongley Parks together. These two areas are adjacent, separated only by City Council legislation and an indistinct fence line. However, Ongley Park had an extensive underdrainage system laid down in 1950, while Manawaroa Park did not receive any such treatment. Up to the time of the investigation, the tile drainage system at Ongley Park had no flow recorded from its outlet. Additionally, both parks still exhibited the same drainage problem, although the relative severity of the problem in either case was difficult to assess as extensive summer rolling of cricket pitches on Manawaroa Park, as opposed to no rolling on Ongley Park, did show up in that infiltration was slower in the former case. No detailed measurement of this was necessary, as observations after a heavy shower before the wet season set in revealed extensive water lodging on the surface of Manawaroa, adjacent to cricket pitches, while no loding occurred at Ongley Park.

While sampling at a later date, areas were found in these parks (as well as in the Massey University No. 1 Dairy Farm*) where the subsoil below 24 inches was almost entirely medium sand. Distinct bands of such unstructured, highly permeable sand had also been located at varying depths, usually below 15 inches. It was felt, therefore, that due to the wide diversification of subsoil textures found on land with an apparently common drainage problem, the location of the problem was unlikely to be associated to an appreciable extent with the subsoil.

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*Shown on the Massey University profile classification map as profiles H_{27} and H_{13}.

II The Profile

Profiles in the Ongley Park area usually consisted of an 'A' horizon, 3 - 9 inches in extent, of silt loam, sometimes with a small percentage of clay. Generally, in the 'B' horizon (which extended down to 18 - 20 inches) the texture ran to a silt loam or a very fine sandy loam with very light to light mottling. As mentioned before, the subsoil below 18 or 20 inches could be anything from a medium sand to a silt loam. No gravel was present in the upper 30 inches of the Ongley or Manawaroa Parks area, but up to $\frac{3}{4}$ inch gravel units were discovered in all horizons on the Massey University No. 1 Dairy Farm and on a private property at Longburn.

A detailed mechanical analysis and profile description are given in Appendices I and II respectively.

III Sampling Sites

The sampling pattern adopted at Ongley Park was selective, rather than strictly randomised, because of the variable nature of the profile and site. Sampling sites had to be selected that:

(a) did not lie over a previously laid tile drain. If care was not taken to avoid this, a non-representative profile could be obtained by sampling in the backfill of a tile trench;

(b) did not include bands of very weakly structured medium grade sand. Such an horizon was not sufficiently stable to support the weight of the core overlying it, and cores taken in such a profile frequently showed a complete collapse of the sandy horizon,

(c) did not include any areas of gravel.

In most instances, avoidance of these undesirable conditions was facilitated by the use of a soil probing spear, but in a few areas, the undesirable characteristic(s) was not discovered until the taking of at least one sample had been attempted, without success. A further factor governing site selection was the need to avoid certain areas such as cricket playing and practice wickets. It was considered that this form of site selection, based mainly on subsoil characteristics, would be unlikely to seriously jeopardize the validity of the results obtained from study of the cores. This attitude is explained on the basis that the drainage problem, as such, was a universal one over the entire area, and that, as discussed previously, the extreme variability of the subsoil condition pointed to a limiting permeability area somewhere in the upper 12 inches of the profile, rather than a specific area of water flow impedence in that portion of the profile lying below 12 inches.

The variability in subsoil textures exhibited by the soil at Ongley Park, and similar areas, if only because of the process of their formation, is typical of many alluvial soils.

SECTION D

FIELD AND LABORATORY TECHNIQUES

I TECHNIQUES AND EQUIPMENT USED IN OBTAINING "UNDISTURBED" SOIL CORES

(a) Attempted Hand Sampling

Initially, it was envisaged that a technique similar to those of Smith and Moodie (1947) or Fitzpatrick (1956) could be employed to remove "undisturbed" columns of soil from the vertical exposed face of the profile. The possibility of roughly shaping a column to be transported to the laboratory, and later trimmed to the final mould, was discarded early on, as the bulk entailed in handling many samples would have been prohibitive. It was felt, therefore, that from a neatly trimmed wall of a large 3 ft. deep pit, using specially shaped tools, a column could be shaped with at least half its periphery cut to the final cylindrical shape. A semicylindrical mould would then be pressed firmly to the column while the latter was cut away from the wall, leaving a little extra girth of soil for final shaping of the cut away portion. It is suggested that it may be necessary in some soils to cut a 6 inch diameter column and coat the outer surface with a reinforcing agent to hold it intact while being finally cut away and removed. The reinforcing agent, before solidifying, would presumably penetrate to a degree, but this effect could be eliminated by trimming the column to 3 inches diameter in the laboratory in the safety of a horizontal working position.

In an attempt to obtain columns in the manner described above, three specially designed tools were used. Each was moulded from a strip of $\frac{1}{2}$ inch by $\frac{1}{8}$ inch strap steel, sharpened along one edge. The first tool, for rough shaping, consisted of a $1\frac{1}{2}$ inch curved portion of the sharpened strip. The curve had a radius of curvature of $1\frac{1}{2}$ inches and was welded to an 8 inch handle. The second tool incorporated a greater proportion of the same curve as in the first. In fact, a semicircle of radius $1\frac{1}{2}$ inches was formed from the strip steel and a handle 6 inches long welded centrally to it at right angles. This tool was used to continue the shaping procedure to a stage where a semicylindrical column was left attached to the wall. The third tool was used in the laboratory, and was an extension of the second tool in as much as it represented $\frac{3}{4}$ of the circumference of a 3 inch diameter circle. Final shaping was thus accomplished with this tool. The edges of the second and third tools were sharpened so as to present a bevel on the outside of the cutting edge only, so that an unbevelled face was always in contact with the core during the shaping operation.

The bulk of the core forming attempted in this manner was carried out in the month of March. As the soil was low in moisture content and often not strongly structured, it tended to shatter easily and hence the stability of columns was low. This made extraction by this method painstaking and unsuitable for large numbers of samples.

(b) Design of Initial Mechanical Sampler

In view of the unsatisfactory results obtained from hand sampling, it was decided to undertake the development of a rotary sampler, similar in basic principle to those of Powell (1926), Kelley et al (1947), Andrews and Broadfoot (1958) and Wells (1959) in that it should incorporate the use of two coaxial tubes, the outer rotating one being equipped with cutting knives, and/or an auger flight.

The sampler first developed, consisted of a 4 inch diameter outer auger tube with a removable cutting head, and housing an inner non-rotative tube. Three cutting knives at 45° to the perpendicular, were symetrically attached around the cutting head in such a manner that they also projected horizontally inwards at the lower end to cut a core 3 inches diameter. On the external of the head, the teeth terminated just below the start of a single flight 45° auger screw which ran the full length up the 4 inch diameter, 36 inch long outer barrel. The basic component of the head consisted at this time of a standard 4 inch water-pipe socket with the knives attached to the outside, and a sleeve welded to the inside, extending from the cutting tip for a distance of $1\frac{1}{2}$ inches upwards.

The inner of the two coaxial tubes was in the form of a 34 inch length of fabricated newsprint-roll core*, split longitudinally. During sampling, the two halves were held together in their original form by adhesive tape or wire binding. These tubes were approximately 3 inches internal diameter with $\frac{1}{2}$ inch walls, giving a 4 inch external diameter. As the outer auger tube was constructed, basically, of 4 inch galvanized water-piping (having an internal diameter slightly in excess of 4 inches) it was a most convenient size to accommodate the inner tube of newsprint core. Coated with clear varnish on the inside to give a more shiny surface, the inner tube was discouraged from rotating by a thrust bearing assembly at the drive head of the sampler (Fig. II). The seating of the assembly was so machined to provide self-centering of the inner tube when inserted in the outer auger rotating cylinder. To remove the inner tube, the cutting head was first screwed off, after unbolting a plate holding one of the cutting teeth against the lower end of the auger flight.

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* Manufactured by Tasman Pulp and Paper Co. Ltd., Kawerau.

The upper horizontal surface of the inner sleeve of the head formed a base on which the inner tube rested piror to the sampler entering the soil. During the sampling operation, as soon as the core commenced entry into the inner tube, it lifted the tube $\frac{1}{16}$ inch so that it lost contact with the horizontal surface of the now revolving inner sleeve, and seated itself in the thrust bearing above, thus largely losing contact with any components of the sampler that would tend to cause it to rotate. Cutting action of the teeth was one of scuffing. As there was no stabilized non-rotative cutting tip, considerable difficulty was experienced in starting the borer without disrupting the surface vegetation.

Despite the use of clear varnish coatings and many common lubricating oils, the core would not slip easily up the inner tube. Further, the thrust bearing assembly, alone, was not sufficient to nullify all rotational tendencies of the inner tube, with the result that often, in formation, the core had been forced to take several revolutions, completely disrupting its original structure. The cutting head was not efficient in that such a cutting tooth arrangement did not adequately clear itself of pulverized material. Some of this material tended to build up as wedges ahead of the teeth. It was considered that this, coupled with a large flat area on the cutting front of the head itself, caused pressure fronts to be built up in the soil in the immediately vicinity of the cutting tip, with a consequent compressive and disruptive effect on the core being formed.

Although it became increasingly obvious that considerable redesign was necessary, certain features of this sampler were satisfactory and could therefore be maintained in any modified form evolved. The attachment linkage to the post-hole borer (Fig. II) with its shear pin was satisfactory (although, through necessity, the shear pin was later enlarged from $\frac{3}{8}$ inch to $\frac{1}{2}$ inch). The thrust bearing and self-centering seating proved to be of adequate design. The split inner tubes of newsprint cores were retained in the modified version of this sampler described below, but not as an integral part of the final sampler.

(c) Modifications to the Design of the Initial Mechanical Sampler

Minor modifications included the provision of bindings of greater strength to prevent the split inner tube from spreading and so contacting the outer rotating cylinder, and the provision of air escape ports (Fig. II) at the top of the auger cylinder.

The cutting head had the internal diameter of the sleeve reduced by $\frac{1}{32}$ inch at the cutting tip, and a further $\frac{1}{32}$ inch, an inch further up. Although this meant the cutting of a slightly smaller diameter core, which would slip more easily in the inner tube, such a core still had to pass from the cutting tip to the start of the inner core unsupported through the cutting head - a distance of $1\frac{1}{2}$ inches. In fact, any swelling of the core during the passage through the head invariably resulted in its contacting the revolving inner surface of the head sleeve. This tended to increase the likelihood of disrupting the core structure. To minimize this, a hardened blade was positioned on the inner surface of the head sleeve so that it removed a sliver of soil from the outer periphery of the core, and passed the material out a slot in the cutting head to be discharged to the outside under the protection of one of the cutting teeth. Although this internal shaving blade kept the core to a constant diameter, despite any swelling tendencies the soil might have had, its very action also increased the forces tending to cause the core itself to rotate and become disrupted.

At this stage, it was considered that a relatively slow speed of rotation was necessary to eliminate undue, and often parasitic, vibrations, but due to the gearing of the drive apparatus, this necessitated low engine speeds of the driving tractor. With such a low speed, maximum torque of the tractor engine could not be approached, with the result that the tractor frequently stalled during the sampling operation. Restarting again itself would increase the likelihood of disruption of the core. By using a more powerful tractor with a similar standard p.t.o. speed, this problem was partially overcome, although the inefficiency of a 45° auger flight on the outer tube of the sampler still greatly increased, unnecessarily, the driving torque requirement of the tractor.

Even with the modifications described, the core, except for the upper few inches, was continually disrupted. In a disrupted state, the core-inner tube friction was greatly increased. This in turn reflected in the unwillingness of the core to move "up" the tube as new portions entered the bottom. The result was that these new portions became compressed and forced laterally against the inner tube walls, thus still further increasing friction, until finally no further material could enter the sampler. This state was relayed to the operator when he experienced extreme difficulty in causing further entry of the boring apparatus into the soil.

To reduce the inner tube-soil friction and also to provide a more stable inner tube, 3 inch o.d. seamless brass tubing ($\frac{5}{64}$ inch walls) was used to replace the newsprint core (Fig. IV, Plate II). The brass tube was split longitudinally, the two halves being repositioned in relation to each other by attachment of 5 brass hinges on each side. By withdrawing the swivel pins of the 5 hinges on one side, the tube could be hinged open along its longitudinal axis.

Remodelling of the cutting head included the provision of a 1 inch bevelled lower extension, and the fitting of new cutters so that the tip of the head formed a sharpened edge and the cutters, extending down to this tip, were able to remove pulverized material more readily and pass it up the three 45° short auger flights on the head to the main 45° flight on the outer tube.

It soon became obvious, however, that some support was necessary for the now $2\frac{1}{2}$ inch travel of the core through the inner sleeve of the cutting head. With this in mind, and the desirability of further aiding the thrust bearing in nullifying rotational tendencies of the inner cylinder, development of the sampler took on its final major phase.

(d) The Design and Performance of a Successful Soil Coring Machine

The sampler consists of an outer augered cylinder with an upper thrust-drive head and a lower removable cutting head, the whole of which revolves coaxially around a non-rotative inner cylinder and soil cutting ring. (Appendix III shows a scale engineering drawing of the sampling tubes.)

(i) The Power and Drive Unit

The machine was developed to attach directly to a standard commercial post-hole boring machine. Principally because of ease of acquisition, a "Halliday*" post-hole borer was used throughout this work. This machine gives a counterclockwise drive at an increasing gear ratio from the power take off of 2:1 through the open right angle drive bevelgears at the head of the machine. The upper stem of the post-hole auger was cut and the commercial auger discarded. A sleeve, welded centrally to the core sampler drive head assembly, was slipped over the cut end of the drive shaft of the post-hole borer and secured with a $\frac{1}{2}$ inch shear bolt. Modifications to the basic post-hole machine were few and relatively simple. To gain more purchase in hand forcing the core sampler into compacted or dry soils, extensions were added to aid the hand levers. As the machine was eventually coupled principally to a 58 h.p. Nuffield 460 Diesel Agricultural Wheel Tractor, extensions were fixed to the hydraulic lift arms of the tractor to pass under the slightly modified frame of the boring machine, so that with a loose fitting hitch to the standard tractor tow bar, the complete boring machine could be lifted clear of the ground by the lift arms. This greatly simplifies transportation of the equipment.

To the sampler drive head assembly, two sleeves, constructed of $11\frac{1}{2}$ inch lengths of $1\frac{1}{4}$ inch galvanized water-piping, were welded, one on each side so that each was parallel in all planes with the axis of the boring tubes. Passing snugly through

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*Manufactured by Macalister Ltd Invercargill these sleeves are 6 ft. lengths of 1 inch galvanized water-piping, which themselves, are attached removably to the frame of the drive unit in a vertical position. During the boring operation, the sleeves, by sliding down and then up these vertical guides, ensure a vertical entry and exit of the coring tubes into and from the profile. No lubrication of the guides or sleeves is necessary, or in fact desirable, as on occasions of mechanical breakdowns, the guides were removed from the unit to allow access to components, and this would not be conveniently accomplished if both were smothered in lubricant. Friction between the unlubricated sleeves and guides is not sufficient to jeopardize the effectiveness of the guiding mechanism. In effect, the vertical guides enforce the action of a parallelogram principlied mechanism incorporated in the original design of the post-hole borer.

Plate I shows the assembled and modified equipment in the transport position.

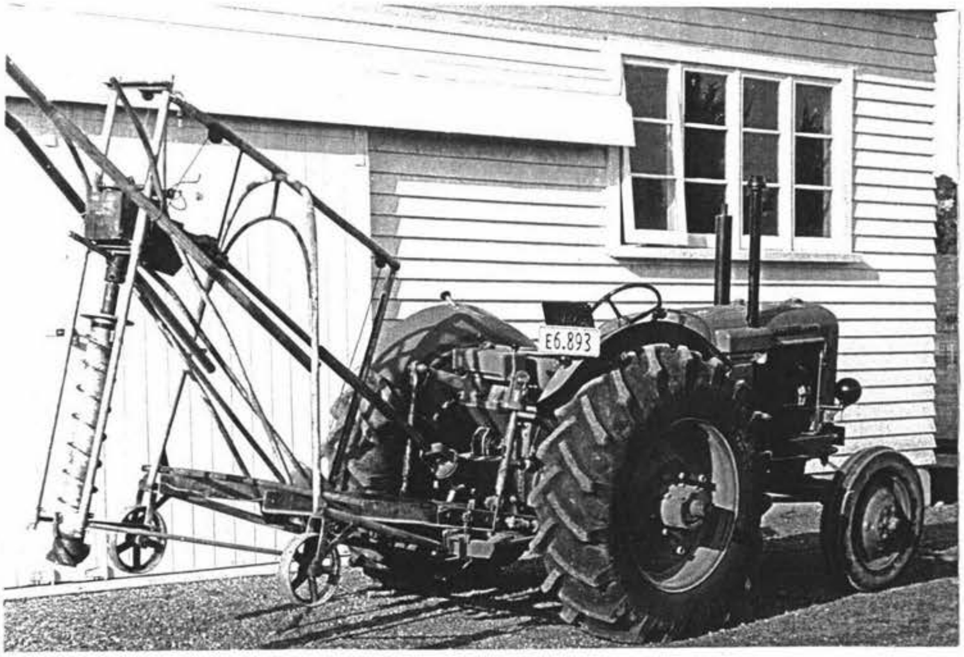


PLATE I

The soil coring machine, together with the modified "Halliday" post-hole borer, raised in the transport position

The Nuffield 460 Tractor, at an engine speed of 1400 r.p.m., delivers a p.t.o. speed of 528 r.p.m.

Consideration was given earlier to the possibility of incorporating another commercial type of post-hole borer. However, it was decided to persevere with the "Halliday" machine as the sample borer was initially designed to suit such a machine, and hence was constructed with a counterclockwise augering and cutting action. No other commercially available machines were designed with counterclockwise action. Additionally, with modifications, the design of the machine enabled satisfactorily controlled vertical entry of the core borer. A disadvantage, however, of this machine was that, through past misuse, certain components had become misalined. The result of this was that the angles presented to the two universal joints in the initial drive shaft were not always identical, giving a consequent double fluctuation of angular velocity for each revolution of the sampler. This misalinement was eventually almost fully rectified.

Despite this, and several other minor limitations, the core samples obtained appeared to be adequate for their specific purpose, so no further time was devoted to perfection of the driving apparatus. No doubt, however, improvements to the same could have provided a more conveniently operated machine, though not necessarily with any appreciable effect on the cores produced.

(ii) The Outer Auger Cylinder and Drive and Thrust Head Assembly

Figure II is a detailed, full scale, partially exploded engineering drawing of the drive and thrust head assembly, together with the upper few inches of both the inner and the outer sampling tubes. It should be noted that those components, shaded in the diagram with closely spaced hatching, remain non-rotative during sampling, while those shown with wider spaced hatching, or no hatching at all, revolve.

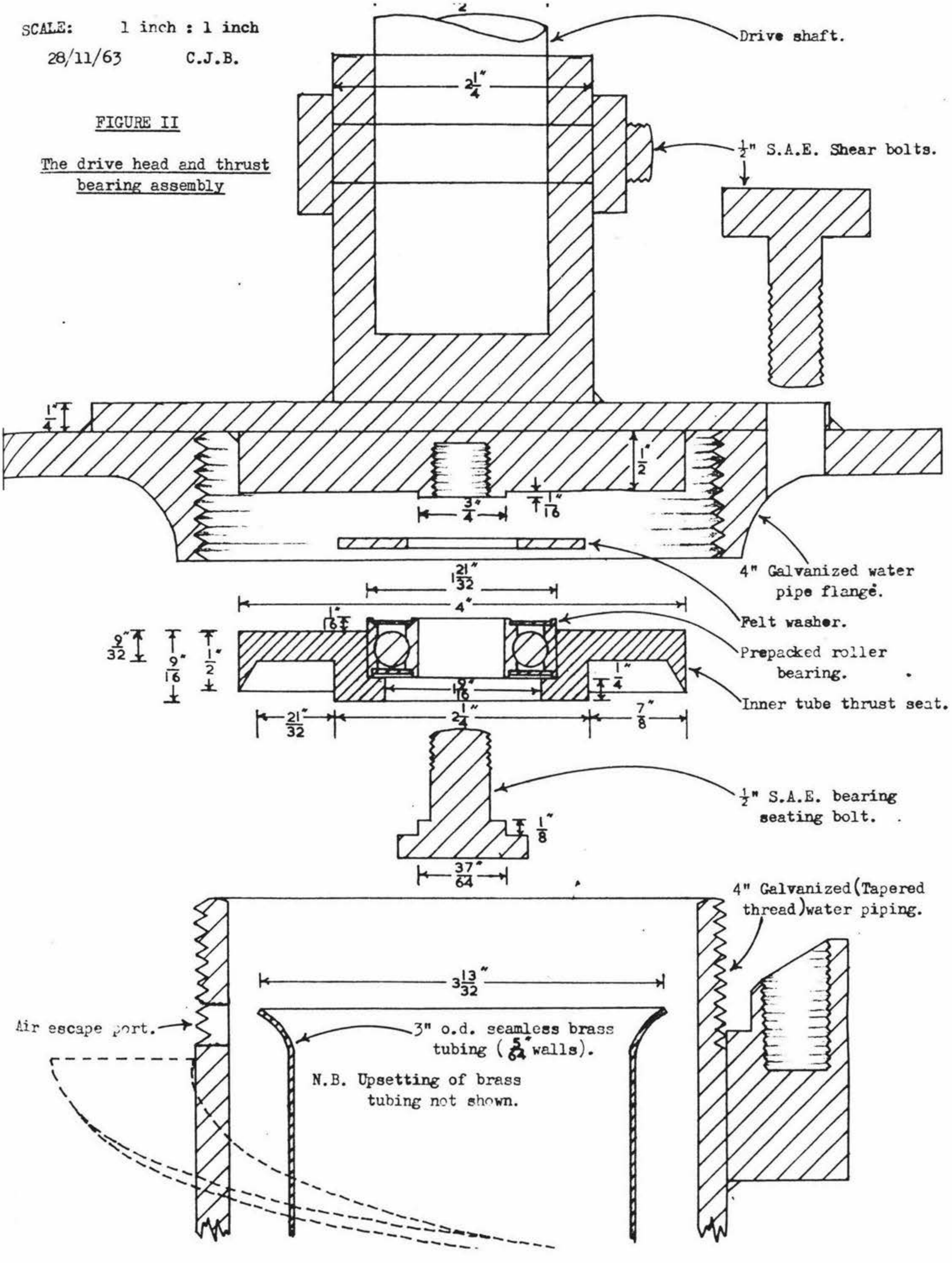
The outer cylinder is equipped with an externally attached auger of 20° pitch. The pitch was reduced from 45° in the initial design to 20°, to increase the efficiency in bringing pulverized material to the surface, and thus reduce the power requirements. This outer auger cylinder, basically of nominal 4 inch i.d. galvanized water-piping with tapered threads, screws into a drive and thrust head assembly. It is prevented from unscrewing during rotation by a shear bolt passing vertically through the outer edge of the drive head flange and into the tapped thread of a block, welded externally to the auger tube. The sampler drive head is constructed from a standard

SCALE: 1 inch : 1 inch

28/11/63 C.J.B.

FIGURE II

The drive head and thrust bearing assembly



N.B. Upsetting of brass tubing not shown.

galvanized 4 inch water-pipe flange, welded to a circular plate. Welded centrally to this plate is a $2\frac{1}{4}$ inch o.d. sleeve, 3 inches long and bored out to $1\frac{1}{2}$ inches to accommodate the axle of the driving unit. Attachment between the sleeve and axle is facilitated by a $\frac{1}{2}$ inch S.A.E. bolt which also serves as a safety shear release if undue, or sudden, torque stress is imposed on the drive unit. Additional safety devices include the shear bolt attachment to prevent unscrewing of the auger tube from the sampler drive head and thrust assembly, and a slip clutch, incorporated by the manufacturers, between the first and second universal joints of the primary drive of the driving unit (Plate I).

Positioned centrally on the underside of the sampler drive and thrust head, is a thrust bearing and seating assembly. Constructed to utilize a readily available prepacked ball bearing unit, it consists of a $\frac{1}{2}$ inch thick by 4 inch diameter circular plate welded centrally to the underside of the large circular plate to which the 4 inch water-pipe flange is welded. The centre of this inner plate is tapped to take a $\frac{1}{2}$ inch S.A.E. bolt, and is machined to provide a lip around the tapped thread, $\frac{1}{16}$ inch high.

The thrust seating device is machined so that its under surface is provided with inwardly tapering vertical walls designed to automatically centre the upper end of the inner soil retaining cylinder when inserted in the sampler. The centre of the upper surface of this thrust seating is machined to a bore which enabled the press fitting of the ball bearing unit into it, so that $\frac{1}{16}$ inch of the unit still protrudes when pushed fully "home". This protrusion of the ball bearing unit coincides with the lip left on the inner plate, and the two together provide enough clearance for the insertion of a felt washer between them in the assembly of the thrust unit. Assembly is accomplished by inserting a $\frac{1}{2}$ inch S.A.E. bolt (with a specially machined head to fit the internal bore of the ball race) through the ball bearing - self seating assembly and felt washer, and screwing it into the tapped thread of the inner plate. In position, there is a $\frac{1}{32}$ inch clearance between the external periphery of the self seating thrust assembly and the inner surface of the auger tube, when the latter is screwed into the sampler drive and thrust head.

The 20° outer auger is constructed of $\frac{3}{4}$ inch by $\frac{1}{8}$ inch strap steel, heated and rolled onto the 4 inch outer cylinder, and welded in place. At the upper end, three $\frac{5}{8}$ inch diameter holes are drilled in the cylinder to allow the escape of air displaced by the entry of the core during sampling.

(iii) The Design and Function of the Cutting Head

Figure III is a detailed, full scale, partially exploded engineering drawing of the cutting head and soil cutting ring, together with the lower few inches of both the inner and outer sampling tubes. It should be noted that, as in Figure II, all non-rotative components are shaded with closely spaced hatching, while all rotative components are shaded with wider spaced hatching or no hatching at all.

The final design of the cutting head is modelled around a nominal 4 inch diameter water-pipe socket, shortened to a length of $2\frac{3}{4}$ inches. A separate sleeve was machined having a basic internal diameter of $3\frac{5}{32}$ inches with inwardly protruding circular ridges at the upper and lower ends of $3\frac{3}{64}$ inches internal diameter. These ridges extend for $\frac{1}{4}$ inch down from the upper, and up from the lower ends respectively (Plate II). The outside of the sleeve was machined with a 30° bevel, extending from a sharp edge at the lower tip to an external diameter of 5 inches, corresponding with that of the external of the water-pipe socket. Where the bevel extended to this 5 inch external diameter, the sleeve was welded internally and externally to the shortened pipe socket. The external weld was later turned down to provide a smooth and continuous finish, and the sleeve thus becomes an integral part of the head. The original upper end surface of the sleeve now forms a $\frac{5}{8}$ inch wide horizontal shoulder in the head.

On the upper unbevelled external surface of the cutting head, short triple start 45° auger flights are welded. Basically of $\frac{3}{4}$ inch by $\frac{1}{8}$ inch moulded strap steel, their presence gives the head an effective external diameter of $6\frac{1}{2}$ inches. This means that the effective external clearance of the cutting head is $\frac{3}{16}$ inch, the difference being in the thickness of the walls of the pipe socket forming the basic structural component of the cutting head. The short 45° auger flights terminate laterally flush at the top of the cutting head, while at the lower end they maintain their external diameter almost the full length of the 30° bevel, terminating laterally in a sharpened cutting surface forming 10° to the horizontal, and extending right in to the tip of the cutting head bevel. As mentioned previously, the pitch of the short auger flights is 45°. However, at the point where the flights meet the sharpened lower edge of the cutting head, small teeth, with an increased pitch, are welded so that soil in their immediate vicinity is cleared quickly and passed to the augers.

All the features of the cutting head thusfar described are shown in Plate II.

When the head is screwed on to the outer cylinder, it is clamped with a removable locking plate to prevent its unscrewing again during the boring operation.

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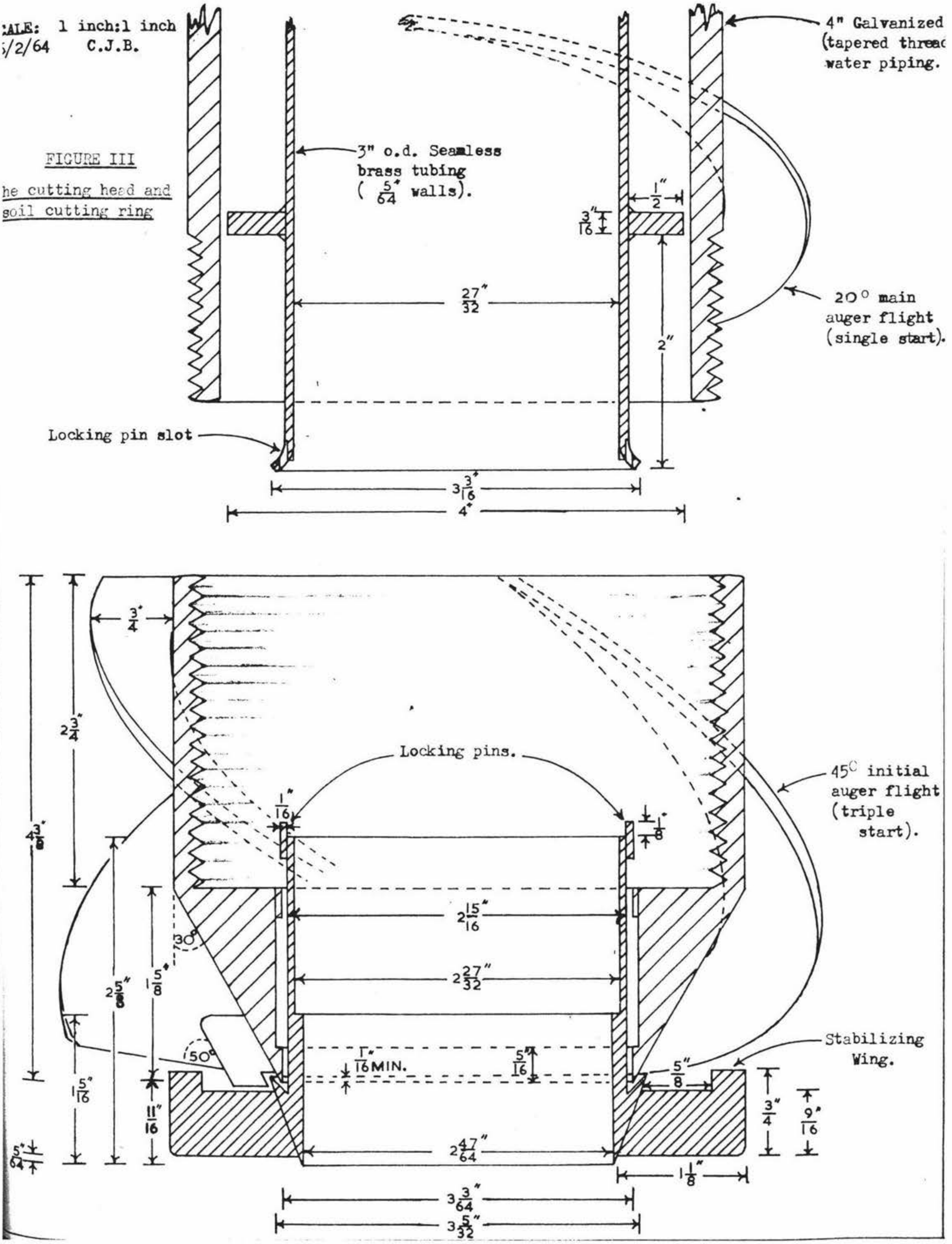
15/2/64 C.J.B.

FIGURE III

The cutting head and soil cutting ring



This locking plate and its backing plate are clearly illustrated in Plate V.

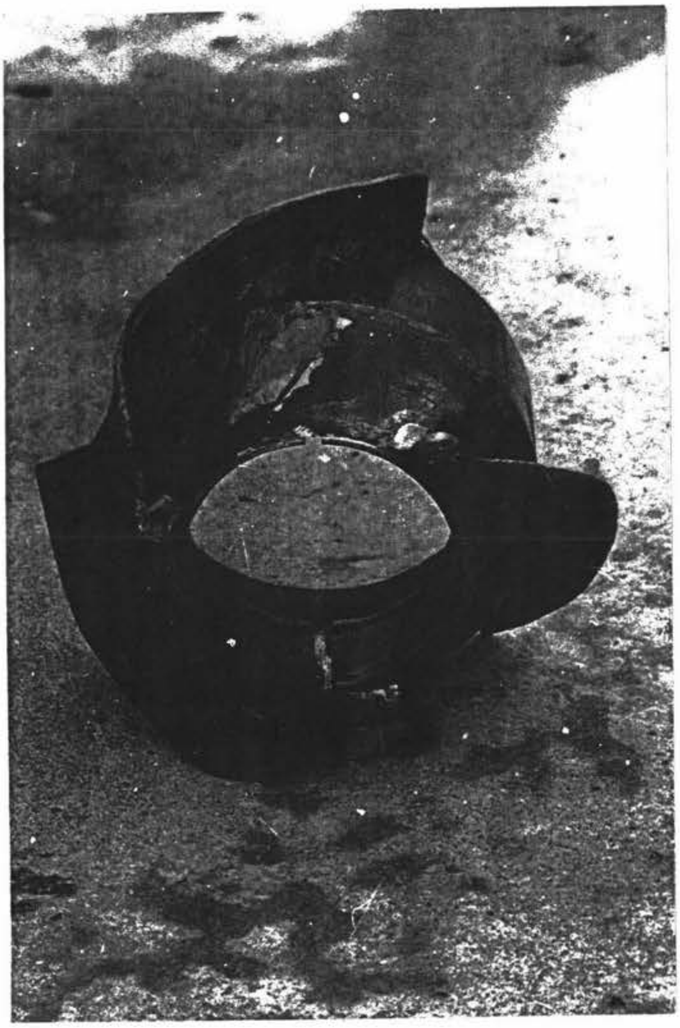


PLATE II

The cutting head

In the initial design with a 45° auger flight on the outer cylinder, the base, to which this clamping plate was attached, formed the terminal point of the main auger flight, so that with the plate in position one of the cutting head short auger flights was continuous with the main auger flight. With the substitution of a 20° main auger flight, the plate base was not removed. Consequently, none of the initial flights now form a continuous auger with the main flight. With the locking plate being able to be positioned behind any one of the three initial flights, and the head requiring $7\frac{1}{2}$ revolutions to be fully threaded on to the outer cylinder, fine adjustments are possible to the internal length of the sampler between the thrust seating and the inner horizontal shoulder surface of the head. This is particularly important in governing the distance that the inner tube must lift off the inner shoulder of the head in order that its upper end may contact the thrust seating above during the boring operation. The amount that the head is screwed on has usually been adjusted to provide an eventual clearance of about $\frac{1}{16}$ inch between the shoulder and the end of the inner cylinder. The circular ridges, mentioned previously, machined on the upper and lower internal surfaces of the head, have two travel slots, 180° opposed to each other and $\frac{3}{16}$ inch wide, milled through them parallel to the axis of the sampler so that the locking pins of the soil cutting ring can slip through the head. Plate II shows one of these milled travel slots.

(iv) The Design and Function of the Inner Tube and Soil Cutting Ring

Figure IV is a detailed, full scale engineering drawing of a transverse section through the inner tube and one of the two spacing rings. As in Figures II and III, the closely spaced hatching denotes components which remain stationary during the boring operation. Plate III shows the closed inner tube removed from the sampler.

As briefly described previously, the inner tube is fashioned from 3 inch o.d. seamless brass tubing with a wall thickness of $\frac{5}{64}$ inch. The original tube was split longitudinally, and along the split on both sides five $1\frac{1}{2}$ inch brass swivel hinges were attached. The heads of the $\frac{1}{8}$ inch brass attaching bolts were counter-sunk and smoothed flush on the internal surface of the tube so as not to disrupt the continuity of the polished surface. All five hinges on one side had their swivel pins removed and replaced with easily withdrawable pins fashioned from 14 guage iron wire. Thus, by the removal of five hinge pins, the tube can be hinged to open and expose the core.

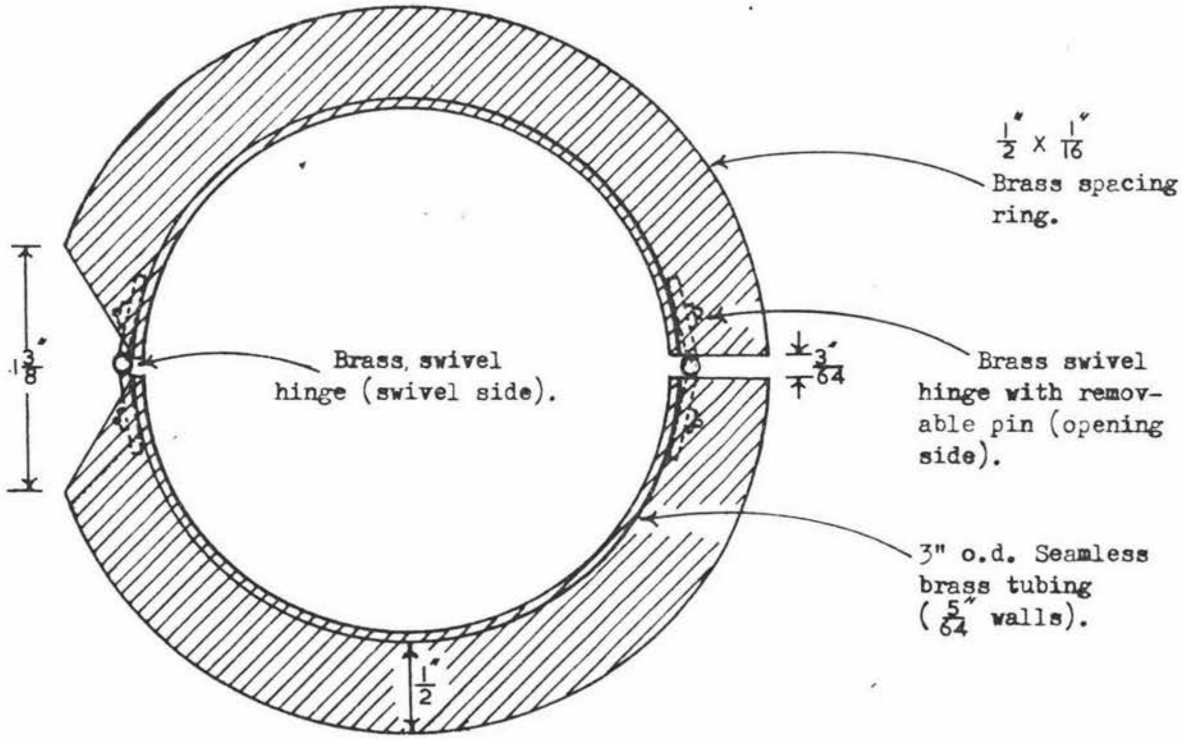
Two flanges, or spacing rings, of $\frac{1}{2}$ inch by $\frac{3}{16}$ inch brass are bronze welded to the outside of the brass tube, 2 inches and $3\frac{1}{2}$ inches from the lower and upper ends respectively. The external diameter of these spacing rings is 4 inches, and they serve to centre the brass tube within the outer cylinder, while being themselves considered to be of small enough external surface area and diameter to minimize any

SCALE: 1 inch : 1 inch

3/3/64 C.J.B.

FIGURE IV

nsverse section through the inner stationary tube



rotational tendencies imparted to them through occasional contact with the outer tube during sampling. The upper spacing ring also guides the inner tube into the self-centering seating of the thrust bearing during assembly. On the hinged side of the tube, suitable portions of the spacing rings are chamfered back to allow the tube to hinge open.

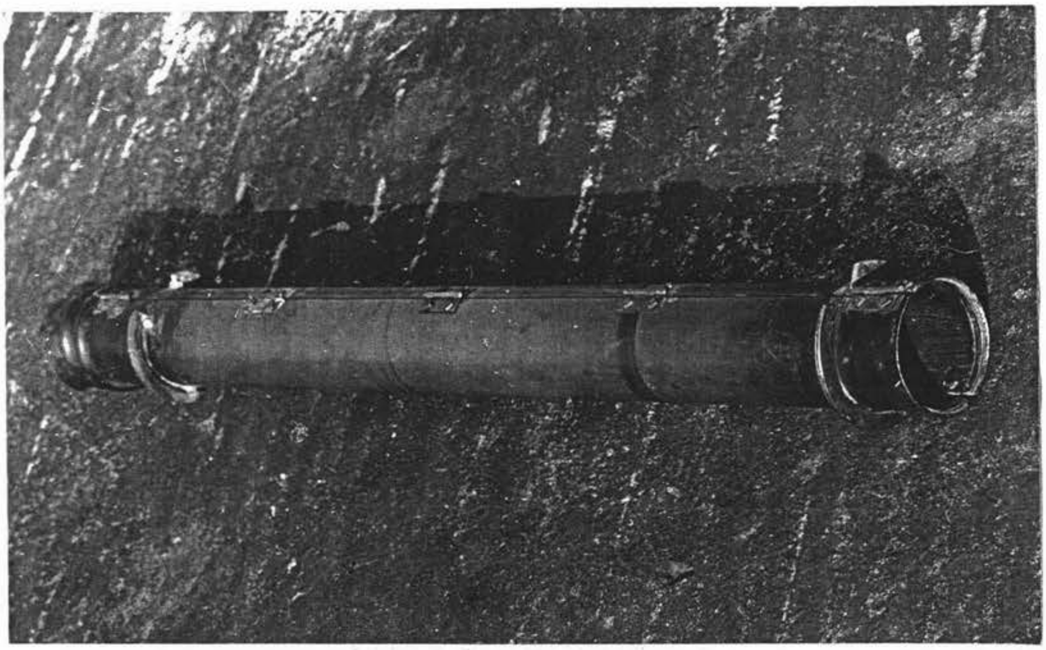


PLATE III

The inner stationary tube

To correspond with the original form of the thrust bearing seating, as designed for the use of newsprint cores as the inner cylinder, the upper end of the brass inner tube is flared to an external diameter of $3\frac{13}{32}$ inches. To ease the passage of the core into the tube, and also to self-seat the upper end of the cutting ring and locking pins, the lower end of the tube is flared to $3\frac{3}{16}$ inches diameter. On the inner surface of this lower flaring, a small shoulder is bronze welded. While the flaring thus acts as a self-seating arrangement for the cutting ring, all compressive thrust, resulting from the downward force applied to the sampler handles to maintain entry rate, is taken on the flat surface of the shoulder. The inside dimension of this shoulder corresponds to the internal diameter of the inner tube and the upper portion of the soil cutting ring. The gap left between the two longitudinal halves of the brass inner tube is $\frac{3}{64}$ inch on either side when the tube is closed. Finally, to adjust the length of the tube, with its flared ends, to 36 inches, the upper portion was heated and upset in a stationary lathe until it had been shortened sufficiently from its original length.

A soil cutting ring is incorporated in the design. Plate IV shows a general view of the cutting ring, and Figure III and Plates V and VI show the ring in position in the cutting head.

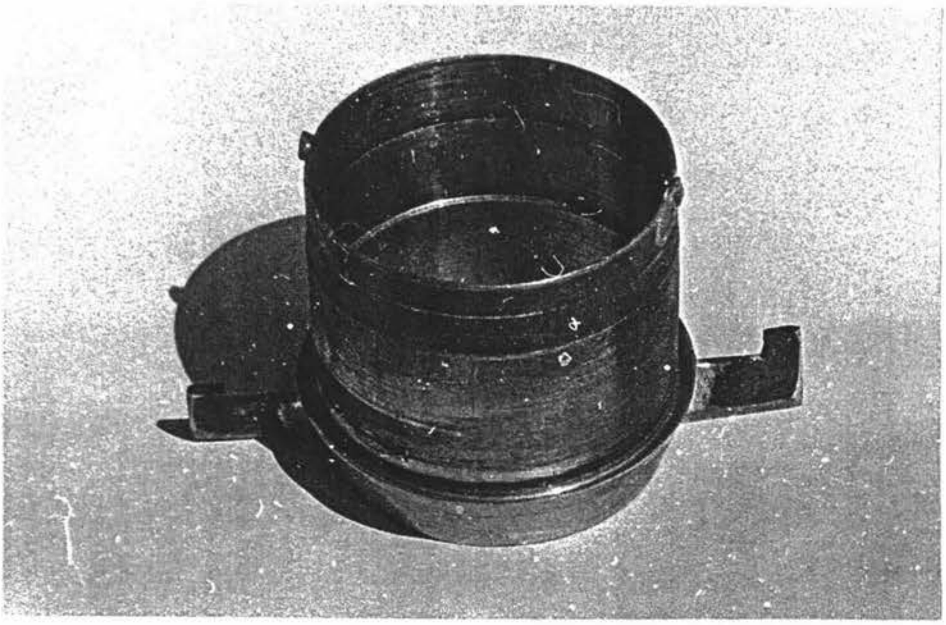


PLATE IV

The soil cutting ring removed from the cutting head

There are five reasons for its inclusion in the design:-

(1) It provides a non-rotative leading cutting edge. Previous workers recommended that for dry or compacted soils, the distance this non-rotative portion protruded beyond the rotating cutting teeth, should be a minimum. Conversely, in more damp or soft soils, the protrusion should apparently be a maximum. However, in the successful design described herein, no variation in protrusion distance is allowed for, as no evidence was found to substantiate the above recommendations. Nevertheless, although such variations appear to be of limited value, there is no reason why detrimental effects would arise from the utilization of designs conforming to these recommendations.

(2) It forms a stable axis about which the cutting head can rotate. This is of immense value in stabilizing the rotary cutting action of the head, especially when starting.

(3) It ensures that the core is actually cut to shape $\frac{5}{8}$ inch ahead of the auger teeth. In fact, $\frac{5}{8}$ inch long core increments are being continually cut by the ring with the same action as the "push in" type samplers described by Fife (1944), Lutz (1947), Thames and McReynolds (1961) and Burnett (1961). As each portion of the core is cut, the material surrounding the previously cut portion is passed to the surface by the cutting teeth and auger system.

(4) It provides a non-rotative passage for the core to pass through the cutting head into the inner tube. To minimize soil - metal friction in both the cutting ring and the inner tube, the ring is machined with the same internal diameter as the inner tube, except at the actual cutting tip. Here, for a distance of $1\frac{5}{16}$ inch back from the tip, the internal diameter is reduced to $2\frac{47}{64}$ inches, thus cutting the core slightly smaller than the bore of the rest of the ring and the inner tube. This $\frac{7}{64}$ inch relief in internal diameter of the cutting ring has proven satisfactory for sampling soils with at least the 'C' horizons high in clay content, and at about field capacity moisture content. However, for drier soils, or soils of less plastic consistency, the diameter is reduced to $\frac{1}{64}$ inch. This, then, ensures a larger diameter core entering the inner tube, with the result that core - tube friction is increased sufficiently to prevent the core from dropping out of the inner tube and cutting ring as the sampler is removed vertically from the profile. With the $\frac{7}{64}$ inch relief, it is impossible to prevent cores from dry silt loam profiles from dropping out of the sampler before they can be recovered intact. These

recommended diameter reliefs for varying soil conditions, types and moisture regimes, substantiate the general findings of Kelley et al (1947) and Andrews and Broadfoot (1958).

(5) It aids greatly the action of the thrust bearing in nullifying any rotational tendencies given to the inner tube through frictional contact with revolving components of the sampler. To accomplish this, the external leading edge of the cutting ring is furnished with two stabilizing wings, 180° apart, each with a slight clockwise lead. As the ring enters undisturbed soil a little ahead of the cutting knives, so too do the stabilizing wings. Thus the ring, which in operation is locked to the lower end of the inner tube, is virtually prevented from rotating counterclockwise by the action of the stabilizing wings in the undisturbed soil.

The cutting ring is machined externally to fit snugly through the cutting head. Friction between the two, during the boring operation, is minimized by reducing their area of contact, the upper and lower internal circular ridges of the head being the only portions coming in actual contact with the cutting ring. Two locking pins, $\frac{1}{16}$ inch by $\frac{1}{8}$ inch, and protruding $\frac{1}{8}$ inch, are bronze welded to the upper, outer edge of the ring, 180° opposed to each other (Fig. III, Plate IV). In operation, each pin fits into an enlarged portion of the split of the inner tube at the point where the shoulder is attached on the inside of the lower flaring. In position, thus, the soil cutting ring and inner tube form a continuous channel from the leading cutting edge to the thrust bearing assembly, the only variation in internal diameter being the relief at the leading edge of the ring.

To facilitate the passage of the locking pins through the internal circular ridges of the head, two milled travel slots are provided, as mentioned previously. Consequently, when the boring operation is completed and the boring machine is being lifted from the hole, the cutting ring will remain in position unless, on stopping the machine previously, the locking pins chanced to be exactly opposite their milled travel slots. The chances of this occurring are very slight, although in the two cases that it did occur in practice, some effort was required to locate and retrieve the ring which had been left embeded in the bottom of a 3 ft. deep hole.

From the leading cutting edge of the ring, the external surface is bevelled at a slightly greater angle to the perpendicular than is the cutting head. This bevel extends upwards to form an edge which overlaps the cutting tip of the head (Fig. III, Plate V). To the bevel, at right angles, are attached the stabilizing wings which have notches cut from their bases to allow rotary passage of the cutting knives of the head.

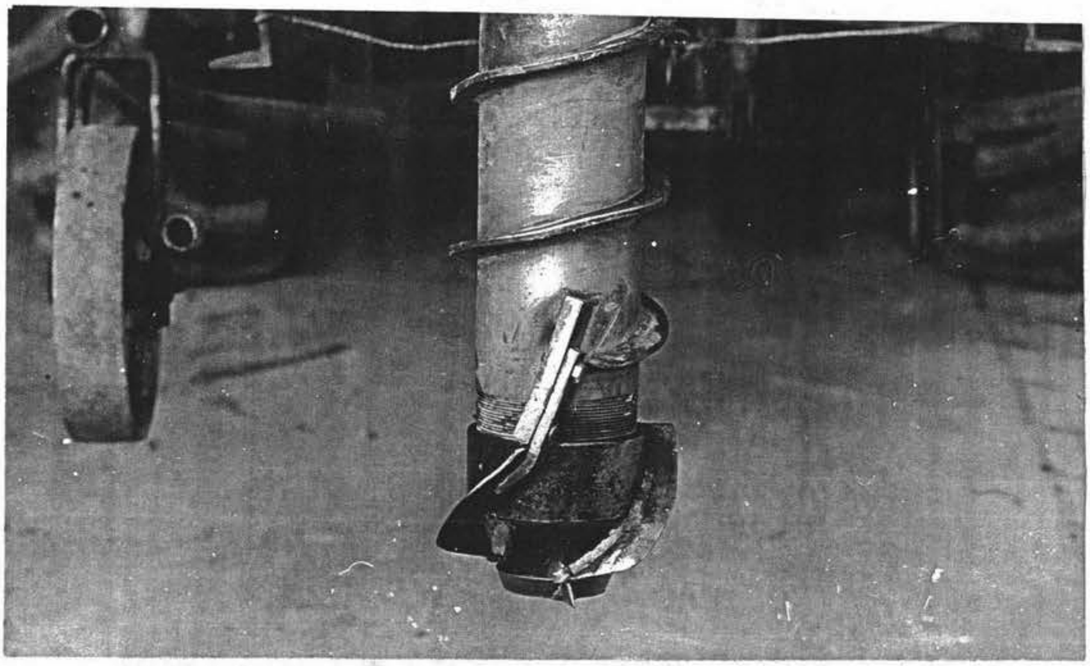


PLATE V

The cutting end of the coring machine

The reason for the bevel overlap (to the extent of a vertical minimum of $\frac{1}{16}$ inch) is to prevent material from being forced between the external of the cutting ring and the internal of the cutting head. If material is allowed to accumulate here, it becomes tightly packed and substantially increases the friction between these two components. So important is the minimizing of friction here, that failure to provide an overlap in an initial experimental design was found to be the sole initiator of the complete failure of the machine to extract unshattered cores. Despite stabilizing wings, under these conditions the cutting ring was forced to rotate to an extent which proved to be detrimental to the core being formed. Andrews and Broadfoot (1958) had also recognized the necessity of avoiding the packing of material between rotative and non-rotative components of a sampler.

Plate VI shows the cutting head (with upper tubes removed) commencing entry into the ground. The top of the soil cutting ring can be clearly seen in the position it would be in to lock with the inner tube. One locking pin is clearly illustrated.

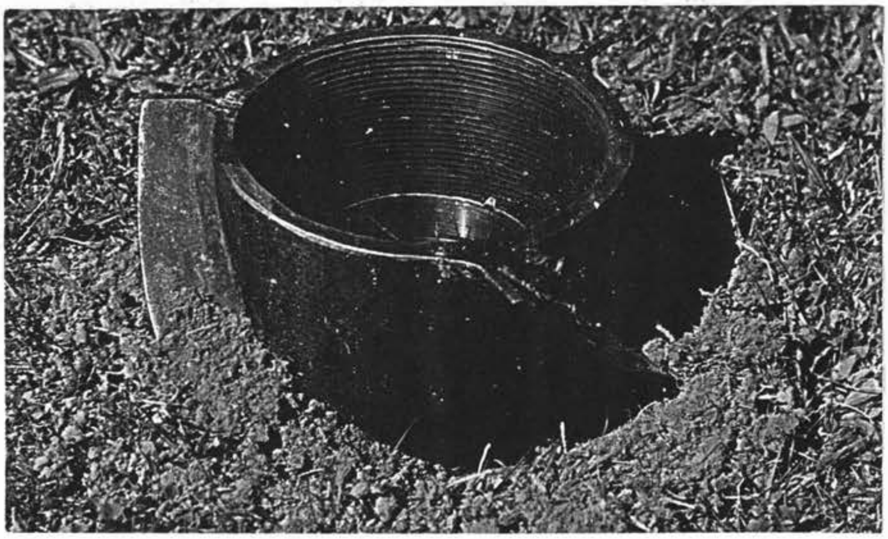


PLATE VI

The cutting head and soil cutting ring commencing entry into the soil

Plate VII shows the cutting ring with head removed. The ring has formed its first portion of the core and is entering undisturbed soil in forming its next portion, while the head has removed the material surrounding the first portion. Note:-

(1) The inner "bowl" shape left by the three cutting knives.

(2) The outer "bowl" shape left by the lower sharpened edges of the three initial auger flights.

(3) The circular groove machined behind the bevel of the cutting ring. The tip of the cutting head revolves in this groove, thus providing the overlap necessary between the cutting ring and the head.

(4) The locking pins 180° opposed to each other.

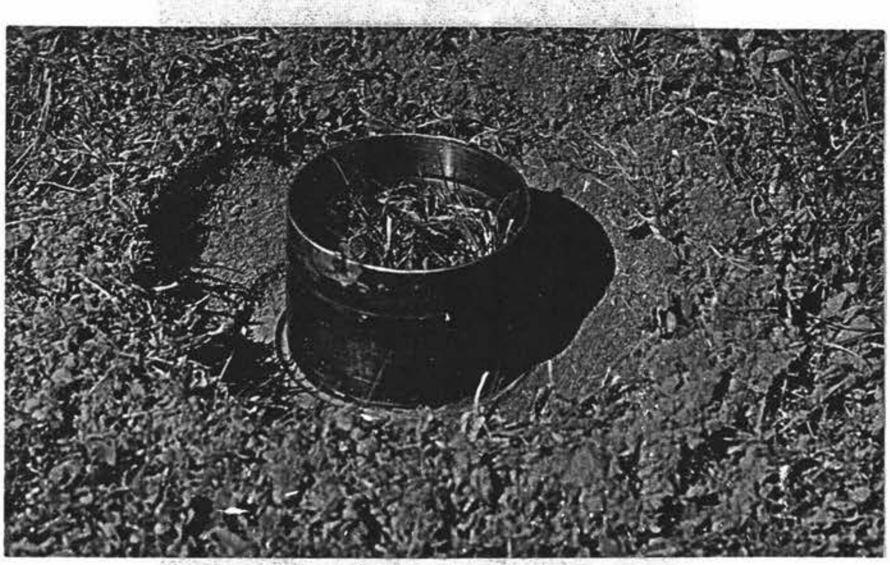


PLATE VII

The soil cutting ring (with head removed) commencing entry into the soil

Plate VIII shows the portion of the core being formed in Plate VII. Note again the double "bowl" shapes left by the cutting augers and teeth, and also the deep bevelled circular groove left by the withdrawal of the cutting ring. At 9 o'clock around the core can be seen the hole left by the withdrawal of one of the stabilizing wings on the cutting ring. A wing, with its clockwise lead, can be clearly seen on the cutting ring alongside. Note also the notch cut from the stabilizing wing to allow rotary passage of the three cutting teeth on the head.

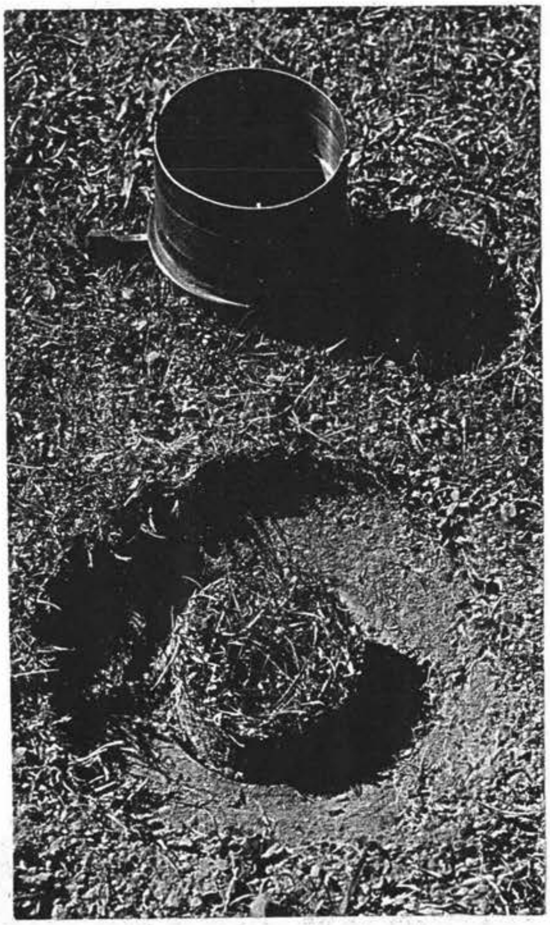


PLATE VIII

The first portion of a core, illustrating the cutting pattern of the head and soil cutting ring

(v) Details of and Comments on Performance

The procedure adapted for collecting a sample was as outlined below:-

(1) The tractor, carrying the sampler on partially raised lift arms, was driven to the selected site for sampling. The inner tube was rotated until the locking pin slots were directly above the milled travel slots on the inside of the cutting head. The cutting ring was inserted through the head, so that the locking pins engaged in their respective slots in the inner tube, after which the ring and tube were given approximately a $\frac{1}{4}$ turn to reposition them with the locking pins anywhere but directly above the milled travel slots in the head.

(2) The whole sampler and drive unit was lowered gently until the cutting tip rested on the ground surface, ready for entry. Preliminary preparations to the actual boring procedure included removal of a cable support to the drive head assembly, and removal of a carrying bar which passed across the lower members of the drive unit, and itself had the extended lift arms of the tractor passing under it.

(3) The tractor operator increased the engine speed to the desired level, engaged the power take off, and with the second operator steadying the extension control levers, the boring operation was underway.

Plate IX shows the sampler in position ready for the boring operation.

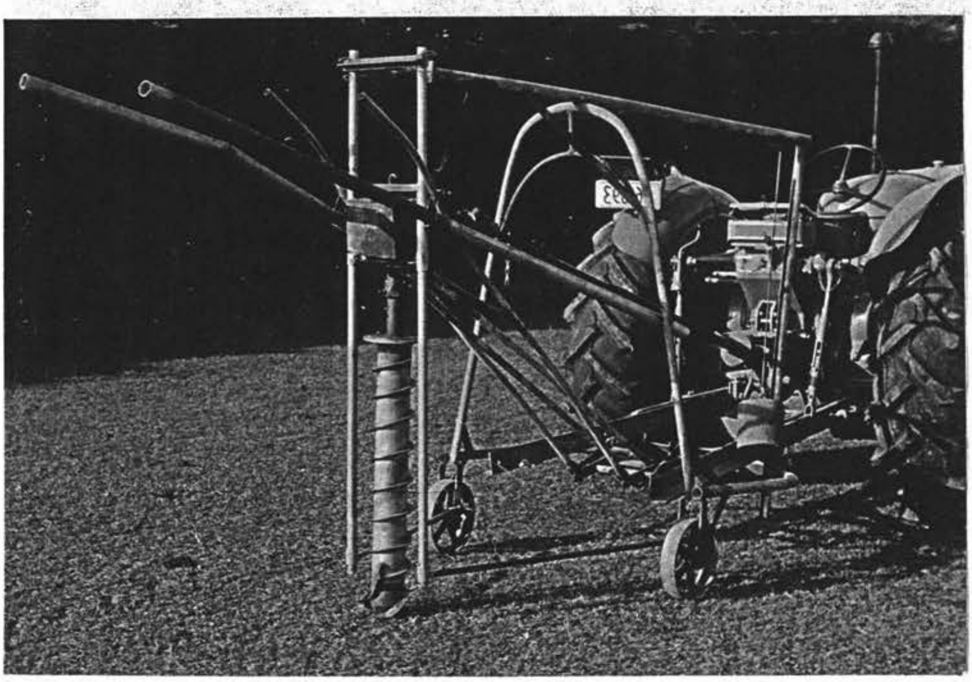


PLATE IX

(4) The sampling operator attempted to maintain a fairly constant feed down rate by adjusting the downward, or even slightly upward, manual force he applied to the extension control handles. When the sampler had penetrated the profile sufficiently, the power take off of the tractor was disengaged.

Plate X shows the sampler tubes at almost full penetration depth.

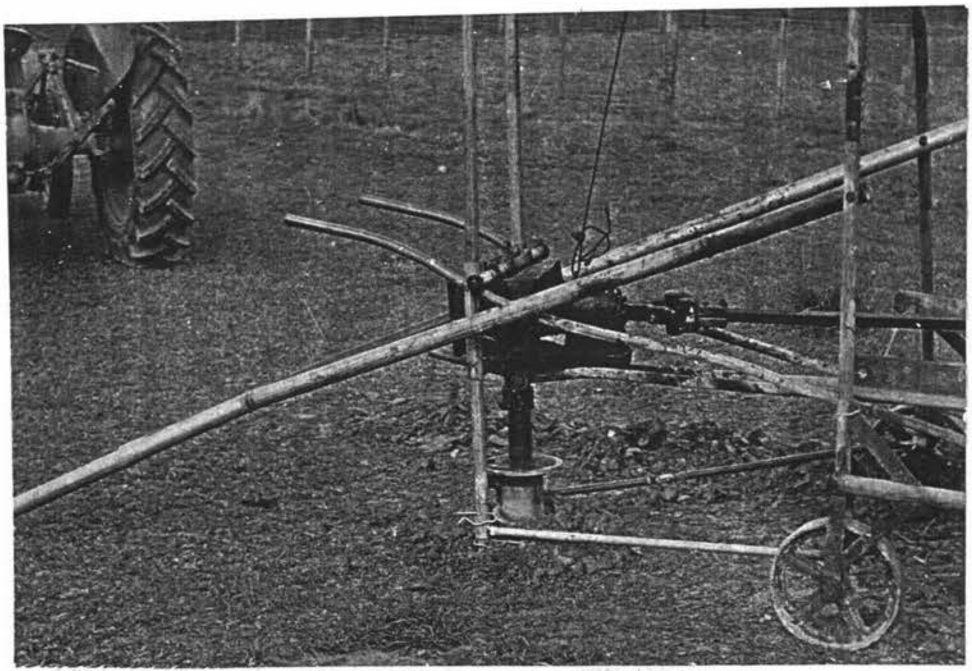


PLATE X

The soil coring machine at almost full penetration depth

(5) The extension control handles were disconnected and positioned in such a way as to allow the hydraulic lift arms of a second tractor to be employed to lift the sampling apparatus from the soil. Once clear of the hole, the drive head assembly was re-attached to the frame of the drive unit by the cable support. The second tractor was removed, the carrying bar reinserted across the drive unit frame, and the whole drive unit frame supporting the sampling tubes was lifted by

the extended lift arms of the drive tractor, until the cutting ring tip was at least 3 feet clear of the ground.

(6) An attempt was made to push the core by hand from the bottom a little further up the inner tube to leave the cutting ring empty. If the core was uncompressed, it would slip easily up the inner tube - in fact, care was often needed to prevent the core from slipping out during either the raising of the sampling tubes from the hole, or the lifting of the whole assembly above the ground surface. If the core could not be moved by pressure from the fingers, it was certain that, in some way, it (or a portion of it) had become compressed longitudinally with consequent expansion laterally, and was thus binding to the walls of the inner tube. Cores of this nature would break when the inner tube was opened later, because a portion would invariably adhere to the brass wall of the tube. Plate XI shows just such a core. Whether or not the cause for the compression of the core could be identified, such cores were discarded, because for percolation trials, they would be of no value.

PLATE XI

A soil core, part of which has adhered to the inner tube

(7) The handle of a large screw driver, or some such similar blunt instrument, was held against the bottom of the core to prevent it from slipping out. The soil cutting ring was then extracted and put to one side. The head locking plate was unscrewed and swivelled back, and the head unscrewed from its position on the outer cylinder. With the head removed, the palm of the hand was substituted for the screw driver handle and the inner tube, housing the core, was slipped out of the auger cylinder and rested horizontally on the ground.

(8) Transfer of the core from the inner tube to its transportation mould was quickly and safely accomplished. The withdrawable pins of the five hinges on one side were extracted and the inner tube opened, leaving the exposed core lying in one side of the tube.

Plate XII shows this, with the transporting mould alongside.

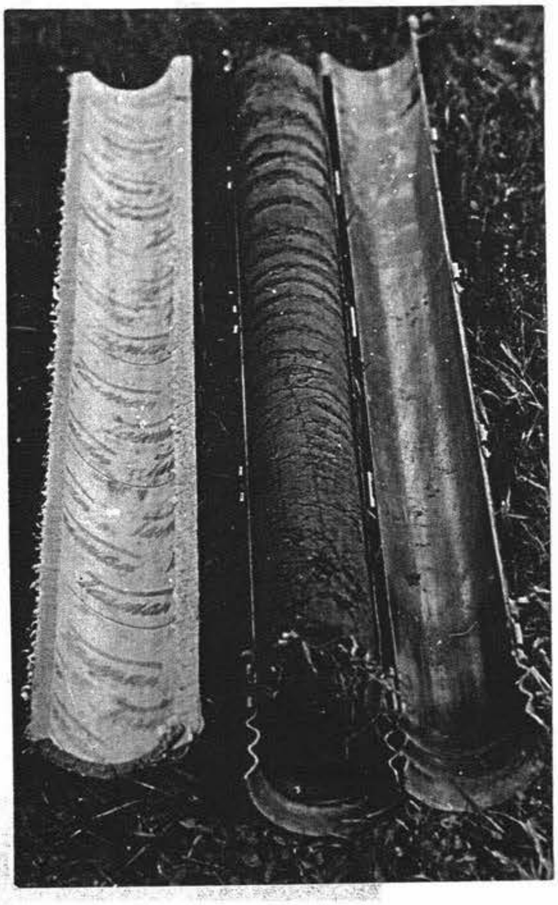


PLATE XII

The core embedded in the opened inner tube

(9) The transporting moulds were fashioned from the 3 inch internal diameter newsprint roll cores, used as inner tubes in previous sampler design. Of fabricated cardboard material, with $\frac{1}{2}$ inch walls, they were essentially the same internal dimensions as the inner tube. They were acquired in 6 ft. lengths, and were split on a wood cutting circular saw so that each portion formed an almost semi-cylindrical mould, the depth of which was 1 inch. It was important to have this depth correct, as it was adjusted so that the mould would fit correctly in the inner tube when removing the core (as shown later). The 6 ft. longitudinally trimmed lengths of the newsprint cores were transported to the sampling site, and each was cut in the field with a hand wood saw to a length corresponding to approximately 2 inches greater than the soil core extracted.

(10) With the inner tube opened, the semi-cylindrical mould of the newsprint core was placed over the exposed portion of the sample (Plate XIII), and the empty side of the inner tube was closed to press firmly on top of the newsprint core to hold it in position.

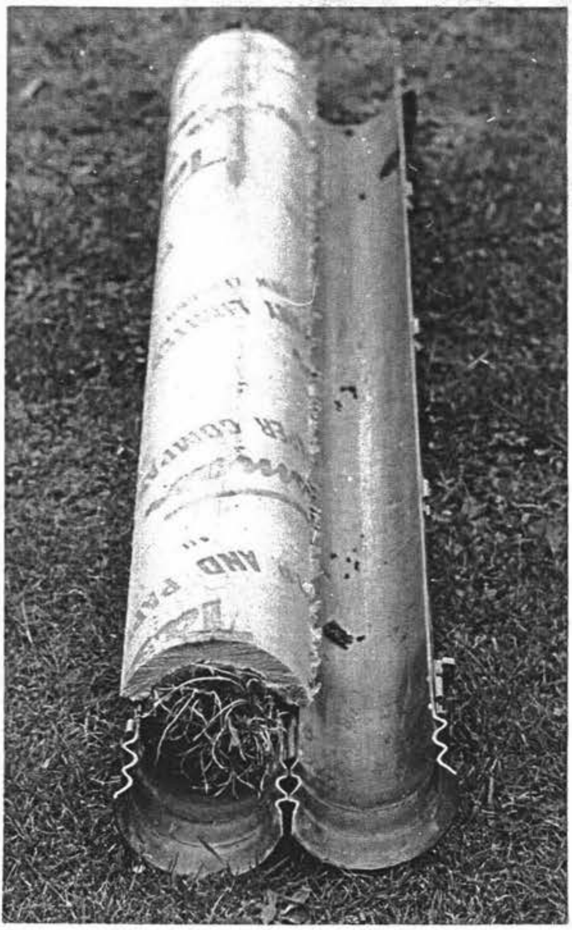


PLATE XIII

The transporting mould placed over the exposed core

(11) Holding this combination firmly, but gently, together, the whole was inverted so that the core was then in fact bedded in the concave of the newsprint core (Plate XIV).

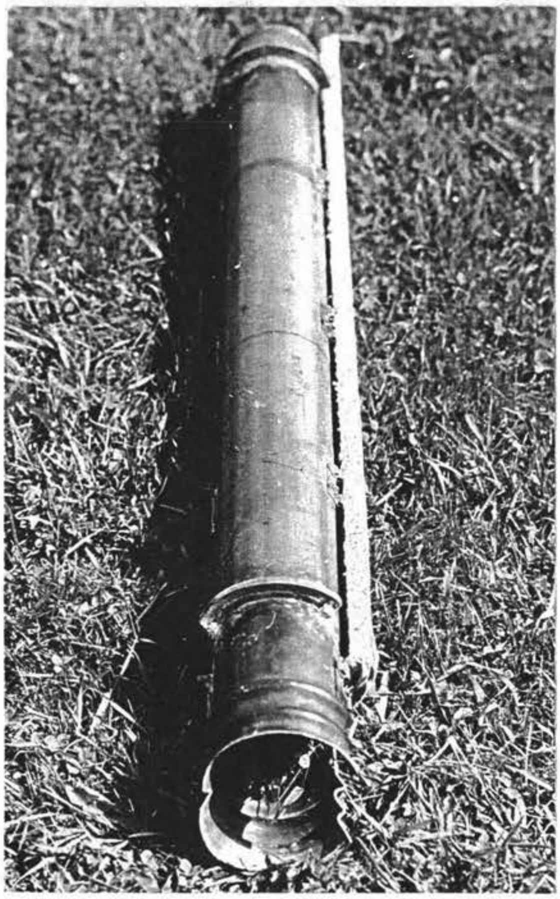


PLATE XIV

The core, mould, and inner tube inverted

The uppermost half of the inner tube was then hinged back and the semi-cylindrical newsprint core mould, with the soil core within, was lifted clear of the inner tube.

Plate XV shows the core embedded in its transporting mould, beside the empty tube.

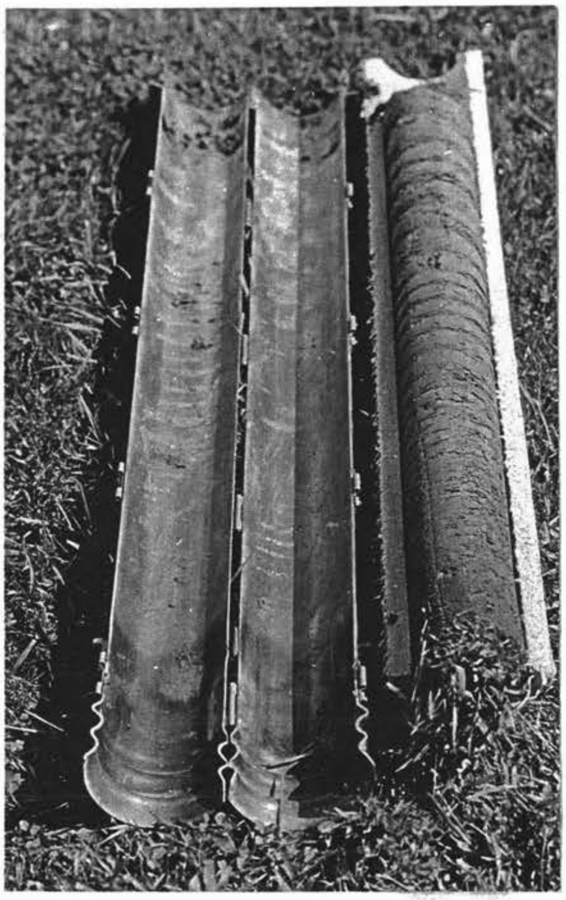


PLATE XV

The core embedded in the transporting mould

(12) An identical semi-cylindrical mould was then placed on top of the exposed half of the core for protection, and the two semi-cylinders were bound together with transparent adhesive tape. Cores thus encased were temporarily stored in a shady place until transportation to the laboratory.

(13) All components of the sampler were cleaned and re-assembled in the reverse procedure to that described above, except that the cutting ring was not reinserted until the operator was actually ready to sample again. There were two reasons for this:-

a. It lessened the likelihood of its loss through inadvertently slipping out during transportation.

b. It lessened the danger of damaging the leading cutting edge.

The entire cycle of operations took, on the average, approximately 11 minutes per sample.

Concerning the speed of rotation of the boring tubes, it was found, by experience, than an engine speed of 1100 r.p.m. on the Nuffield 460 Tractor was desirable in sampling Ongley Park soils at moisture contents approaching field capacity. This engine speed of 1100 r.p.m. eventuated in a speed of rotation of the auger tube of approximately 210 r.p.m. In drier conditions, increasing the engine speed to 1200 r.p.m. (auger speed approximately 230 r.p.m.) seemed beneficial. Through limited experience in other soil types, no general recommendations can be made concerning desirable auger speeds under varied conditions. It was considered, however, that a speed approximately 210 r.p.m. was sufficient in most cases, as samples were also extracted successfully at that speed from a quite heavy mottled clay subsoil close to field capacity. It was evident from experience, and also from the recommendations of Kelley et al (1947), that the relief in diameter offered behind the leading cutting edge was a more important factor in sampling different soil types at different moisture contents, than was the speed of rotation.

The 45° pitch of the initial auger flights, and increased pitch of the cutting teeth, were designed so that the cutting action of the head was more one of scuffing than shaving. It was considered that a substantially decreased pitch would have had the effect of shaving a sliver of soil at the cutting knives. Consequently, the rate of entry would be largely governed by the material through which the head was passing. Thus, a moist plastic clay could have tended to "pull" the sampler in, while a drier and more compacted horizon could have been difficult to penetrate at all, and a feed-down mechanism, similar to that of Kelley et al (loc.cit.), would have had to be incorporated. However, with the scuffing action incorporated in the successful design, entry rate was governed, principally, by the pressure from the operator on the extension control handles. With experience, an operator could guage the compaction throughout the profile, and thus apply considerable pressure when boring in dry, compacted material. Similarly, in soft material, the constant entry rate could be maintained by reducing the downward pressure, and in extreme cases, such as pure sands, it was sometimes necessary to partially support the weight of the sampler to govern its entry speed.

Although the feed-down rate of the head was easily governed, if material became wedged between the main auger flight and the wall of the hole, the main auger itself tended to screw the sampler in, and this could be nullified only by a considerable upward pressure from the operator. In the earlier design, the compacting and wedging of material between the auger cylinder and the hole wall was exaggerated because of the non-vertical entry angle of the tubes. Despite the parallelogram principled mechanism on the drive unit, without the aid of guide sleeves it did not ensure a vertical sampling path of the boring tubes. The entry locus of the cutting tip tended to be more in the form of a gentle arc than a vertical line.

As mentioned previously, under certain conditions the core tended to stick to the inner tube. It should be noted that all the factors leading to this condition were not positively identified, but observations and trials indicated that:-

(1) Very wet or compacted clays would often swell upon entry into the inner tube. Possibly, under such conditions, the relief offered in the cutting ring was insufficient.

(2) A 2 - 3 inch layer of very wet and/or compacted clay was often sufficient to swell and bind to the walls, thus greatly increasing the core - inner tube friction at that point, and leading to compression of the underlying portion of the core in attempting to force the binding layer "up" the tube.

(3) Horizons of sand collapsed and themselves became wedged tightly against the inner tube walls with the same effect as a damp and/or compacted clay layer.

(4) Any rotation of the inner tube during sampling (in some soils as little as 180°) could have the effect of twisting the core and thus upsetting its stability, often with the further effect of increasing the tendency for the soil to bind to the inner tube. It will have been previously noted in Plate XI that no square shoulder is visible on the lower flaring of the inner tube. This lack of a flat thrust face for the cutting ring to bear upon in the previous sampler designs, was found to be contributing greatly to the formation of cores which were binding to the tube walls. With increasing downward force by the operator, the cutting ring was forced up the flaring a little more. In extreme, this eventuated in the cutting head tip coming in contact with the cutting ring overlap bevel, thus greatly increasing frictional contact between the two components. The end result of this condition invariably was that the inner tube, despite the stabilizing wings, was induced to partially rotate, with the effect of disrupting the core structure and causing it to bind to the tube walls. As can be seen in Plate XI, diagonal shear planes in the core indicate the extent of structural disruption caused by the partial rotation of the inner tube. By the addition of the square shoulder to the flaring, these conditions

were avoided, and almost all instances of binding between core and wall, except where they were due to an inherent weakness in the profile, were eliminated.

It must be stressed, however, that in practice, generally, no single cause could be attributed to the initiation of binding. Rather, several of the complementary factors described above invariably contributed to this undesirable state.

Attempts to overcome these binding tendencies with lubricants followed basically the recommendations of Stace and Palm (1962) and Palm and Sykes (1962). However, in New Zealand, the product "Shell G.B. 800" was not available, and silicone grease and "spray on" cooking fat coatings on the inner surface of the inner tube were found to be of little, if any assistance. Additionally, the effects of water as a lubricant were investigated. Immediately prior to the entry of the boring tubes into the profile, the spaces within the cylinders were filled with water. To accomplish this, the nozzle of a hose was placed against one of the air escape ports (Fig. II, Plate IX) and the tubes filled. As the boring operation proceeded, water, displaced by the formation of the core, spilled out these escape ports. With this technique, the borer was working in a continuous slurry, although the core itself was not reduced to slurry conditions due to the short length of time it was exposed to the water. Well drillers have, for a number of years, employed water lubrication techniques in extracting cores of soil. However, in the main, their cores have not been required to be structurally "undisturbed". The technique described by the author, in general, was found to be unsatisfactory and did not prove to be of sufficient lubricating value to warrant its continued use.

It was found more satisfactory to select profiles which exhibited the poor drainage condition but did not contain atypical bands of unstable material, or which were at an optimum moisture content at the time of sampling. The optimum subsoil moisture content for satisfactory sampling of Ongley Park soils was found to lie between 18% and 25%. An optimum at the subsoil level was of more value as a guide than at any other level in the profile, as compression forces arising from the overburden of the core above were more pronounced in the subsoil. Other steps taken to minimize the sticking of the core to the inner tube were in taking care to ensure a constant feed-down rate during sampling, and the avoidance of too rapid an overall feed-down rate. In this latter respect, it was sometimes difficult for the operator, when guaging a soil condition inhibiting the normal feed-down rate, to ascertain whether the cause was a compacted layer through which the sampler head was passing, or a direct result of the core having binded to the inner tube wall. In the latter case, such an occurrence caused the travel of the core "up" the tube to be restricted, and this had repercussions in that increased pressure was required on the extension control handles to maintain feed-down rate. If the restriction was due to the former cause, the core was not likely to suffer, but in the latter case, already the core must have been adversely compressed to bring about this condition. Perhaps though, the most important factor of all was to ensure the non-rotation of the inner tube, with its disruptive effect on the stability of the core, by appropriate design of the boring mechanism, thrust mechanism and stabilizing wings.

Performance Testing Criteria

One of the most valuable single properties of a sample which will indicate a machine's effectiveness in obtaining "undisturbed" cores, is the specific recovery ratio. This, according to Northey (1963), is the ratio of the length of the core extracted, 'L' , to the depth of the hole, 'D' , from which it was extracted. Tabulated below are data obtained from use of the sampler, described above, in extracting cores from a profile with a subsoil of high clay content.

Sample Number	L	D		Specific Recovery Ratio
1	30.75 inches	31.25 inches		0.98
2	30.75	31.00		0.99
3	32.00	32.50		0.98
4	31.75	31.75		1.00
5	31.50	31.75		0.99
6	29.75	30.50		0.98
7	29.75	31.25		0.95
8	31.50	31.75		0.99
			MEAN	0.98

TABLE IV

The specific recovery ratio of cores extracted by the sampler

In practice, having established a specific recovery ratio very little removed from unity, continual detailed data of the core and hole dimensions were not kept.

With repeated coring, it became quickly obvious when a core was shorter(even as little as 2 - 3 inches) than the hole from which it had been extracted. Additionally, when a core was removed from the sampler, if it was seen that a band of sand was present, the specific recovery ratio was then determined as it was most likely that the core had become shortened during extraction. Cores found to exhibit a specific recovery ratio much below 0.95 were discarded.

Another indication of the lack of disturbance, although qualitative, was nevertheless very conclusive. By chance, during sampling, the cutting edge of the soil cutting ring would sometimes cut through earthworm channels, in such a manner that it could be clearly seen, on examining the sample externally, no disruption of the original soil had occurred. Plate XVI shows, macroscopically, such earthworm holes which were dissected for part of their length by the cutting edge.

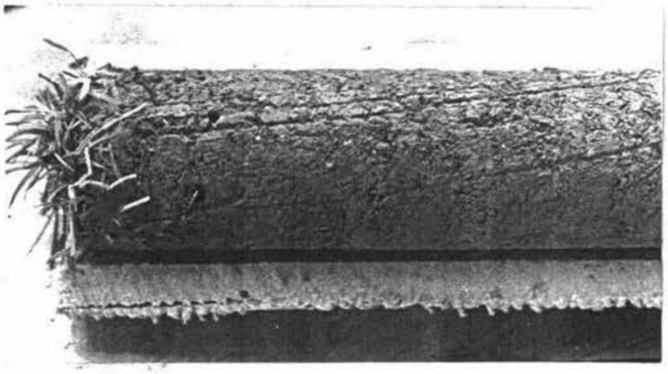


PLATE XVI

The upper portion of an "undisturbed" core, illustrating severed earthworm channels

Close examination revealed that the concave portion of the channel still remaining was unshattered. So clear was this evidence that the smoothened surface left by the passage of the earthworm was unbroken, and this within $\frac{1}{32}$ inch of the periphery of the core. Plate XVII is a greatly enlarged photograph of three earthworm channels cut diagonally across by the sampler, one of which in particular, clearly illustrates the undisturbed smoothened wall left by these soil organisms.

PLATE XVII

Greatly magnified view of earthworm channels, severed by the leading edge of the soil cutting ring

The state of the surface vegetation left by the sampler was extremely desirable. As can be seen in Plate VIII, the vegetation on the core surface was left in a healthy and undisrupted condition. Often, on examination of a core, fine, deep grass roots could be seen protruding from the 30 - 36 inch deep subsoil end.

On almost all cores, the formation of distinct rib-like, circular grooves from perhaps 18 inches downwards seemed to be unavoidable (Plate 12). As it was considered that their presence did not materially affect the internal physical properties of the core, no further time was devoted to eliminating this condition. It doubtless arose from the slight variations in the angle the cutting face of the soil cutting ring made with the perpendicular during entry into the soil. Isolation of the cause, or causes of the angular variation was not conclusive. However, it did seem distinctly possible that the head locking plate and base assembly on the lower end of the auger cylinder (Plate V), because of their asymmetry with the rest of the auger cylinder and head, could have caused the sampler head to move slightly laterally with each revolution. This effect would be magnified in the denser subsoil where accumulation of pulverized material would also be greater than at the shallower depths. Packing of such pulverized material would mean a more confined space in which the auger must rotate. Hence, if the lock plate and base assembly built up a wedge of soil ahead of it in the subsoil, it could well be accentuated sufficiently to give rise to the grooves on the core. From examination, one groove appeared to correspond to one revolution of the auger tube. It was found that the so-called grooves were, in fact, one continuous spiral groove which seemed to increase in pitch at depths in the profile where it had been noted that the entry rate increased during sampling. However, the explanation of its formation appears to be somewhat more complex than the suggestions made above, as at least one another set of workers (Bloodworth and Cowley 1951) have reported similar effects with the essentially symmetrically designed "Kelley" sampling machine. Nevertheless, little doubt is attached to the assumption that the boring machine described above would have been improved by the elimination of the asymmetry of the locking plate and base assembly.

On many early cores, it was apparent that the inner tube had not, in fact, remained entirely non-rotative. In addition to, or instead of diagonal shear planes appearing in the core (Plate XI), small diagonal peripheral channels (indicating perhaps one half of a revolution of the tube) were often noticed. Normally, the indentations of these lines was brought about by small fragments of vegetative stubble being rolled along between the core and the inner tube as the core passed "up" the tube. Plate XVI illustrates the lines caused in this manner in early cores. This rotational tendency was eliminated by increasing the surface area of the stabilizing wings on the cutting ring and providing a flat thrust shoulder in the lower flaring of the inner tube. Plate XV illustrates channels, now almost parallel with the axis of the core, as a result of these modifications. However, as the uncut soil from which these wings derived their stabilizing effect could be of variable compaction and resistance to penetration, it was little wonder that the stabilizing effect of the wings was more pronounced in one soil sampled, than in another, and indeed, there was often a variation between individual samples from the same soil type.

A unique qualitative test devised to establish the degree of undisturbance of the core was that arranged as a final trial for the sampling machine. A hole, 2 ft. deep and measuring 18 inches by 3 ft., was excavated and entire portions of the smoothed walls and floor painted with commercial plastic paint (Plate XVIII). The hole was then refilled and rammed to compress the backfill to a compaction approximating the undisturbed soil adjacent to it.

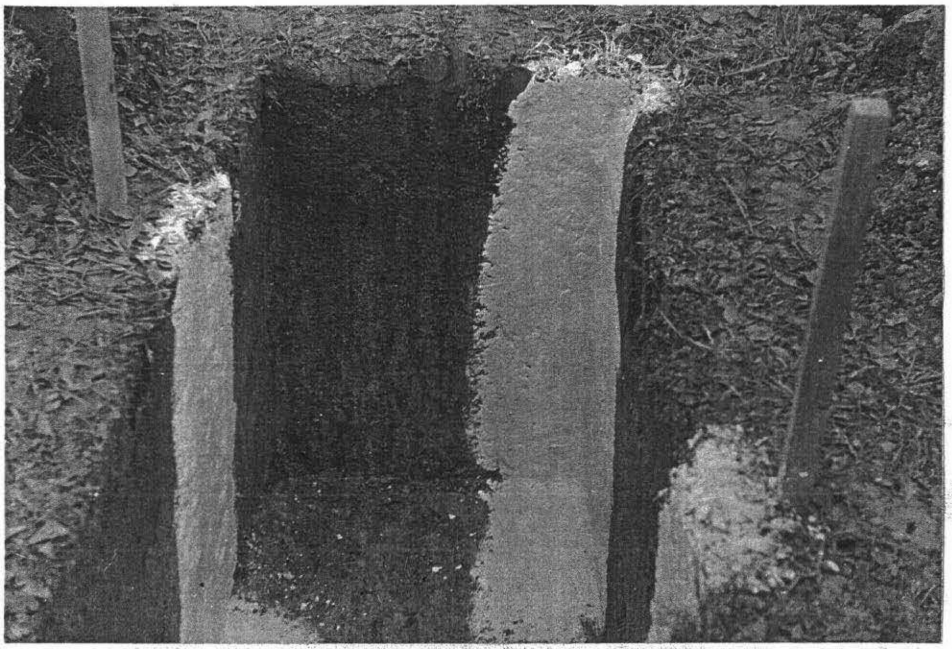


PLATE XVIII

The excavated "paint hole", with entire portions of the walls and floor coated with plastic paint

A possible limitation of the method was that when sampling, with half the core coming from the undisturbed soil and half from the adjacent backfill, excessive variability of material cut in each revolution of the sampler could have contributed to some disruption of the core. However, no subsequent evidence was found to support this suggestion. It was also felt that the very nature of the ramming procedure in compacting the backfill could itself have disrupted the paint surface. However, again, this was not seen as a serious limitation to the effectiveness of the technique. The procedure was to attempt to obtain a core made up for half its thickness of the undisturbed soil with the painted surface, and the other half, of the adjacent backfill. Examination of the core revealed whether or not the sampling operation was sufficiently effective in obtaining a core with the paint line still in tact throughout it's length. Moreover, any twisting of the core during extraction was readily observed when the backfill portion of the sample was carefully picked away in the laboratory to expose the painted surface. Plate XIX shows two cores taken in such a manner and picked down to the paint in the laboratory. The remaining portion of the cores shown represent the portions of the samples which included the undisturbed soil and its painted surface.

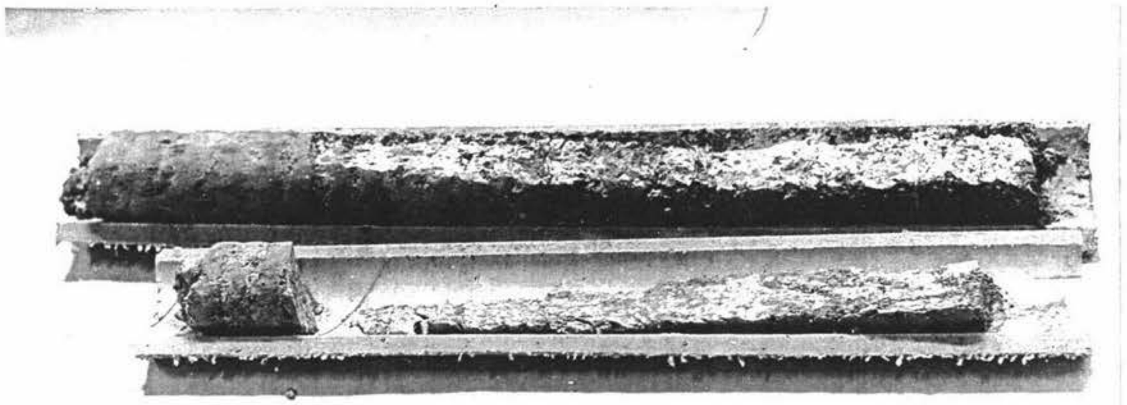


PLATE XIX

Two cores extracted from a "paint hole" and picked down to the painted surface of the original undisturbed soil

The lower core in Plate XIX was taken midway along the painted wall of the hole. Partially due to the fact that the hole wall was not exactly vertical, and that the boring tubes may not have entered the profile altogether vertically, the painted surface was not incorporated entirely in the centre of the sample. However, the avoidance of disruption of the paint (both on the wall and bottom of the hole) and the obvious avoidance of twisting in the core were self-evident of the ability of the machine to extract "undisturbed" profile cores.

The upper core in Plate XIX was extracted from the corner of the hole and incorporated two painted sides and the painted bottom. Unfortunately, the positioning of the sampler on the surface was a little inaccurate, and only a small portion of one of the painted walls was included. However, again the evidence was in favour of the sampler. In this core, especially, a slight (perhaps $\frac{1}{8}$ of a turn) twist was apparent in the core near the bottom of the "hole". This, in fact, was a clockwise twist, and can only have been caused by the stabilizing wings with their slight clockwise pitch. It would appear that as the wings entered the more dense subsoil, their stabilizing action (which was dependent on the uncut soil bearing on their surface) was over emphasized to the stage where, in fact, they caused a clockwise movement of the cutting ring and inner tube.

It is worthy of mention that picking of the backfill from the paint in the core must be carried out while the core is still relatively moist, otherwise it is difficult to separate the soil from the paint.

It is considered that this test was an extremely critical one and required a high state of effectiveness of the sampling mechanism to achieve positive results.

II TRANSPORTATION, STORAGE AND PREPARATION OF THE CORES PRIOR TO THE LABORATORY INVESTIGATION OF THEIR HYDRAULIC CHARACTERISTICS

(a) Transportation

Cores contained within the protective moulding of the two halves of split newsprint cores were reasonably stable and well-protected from physical damage. However, every precaution was taken to ensure that unnecessarily rough handling was avoided. Sudden movements or bumps could lead to cracking of the cores. Unless severe, lateral cracks were usually considered to be of little significance, as, once encased in paraffin wax, their presence did not seriously affect the hydraulic conductivity of the core as a whole. Where a crack tended to run diagonally across the core, however, water was likely to channel down the crack and thus largely by-pass the pore system adjacent to it.

The moulds, containing the soil cores, were normally bedded in excess soil contained in the transporting car trailer, and in this manner they were conveyed to the laboratory. Wet, clean sacks were placed over the cores on the trailer to prevent excessive loss of moisture arising from prolonged exposure to sunlight or air movement. It was found that core moulds and their cores should not be left under the sacks for more than half a day at a time, as the fabricated moulds tended to swell as they absorbed moisture from the sacks, and this could be detrimental to the soil core within.

(b) Storage

Cores were usually treated with paraffin wax on arrival in the laboratory, but where it was necessary to store them for longer than a day, they were sealed in polythene bags, together with porcelain basins containing saturated cotton wool to help maintain the humidity within the polythene bags. Even with this manner of storing, it was recommended that cores be waxed as soon as possible, as the surface vegetation would not survive long in such conditions.

(c) Trimming

Prior to waxing, each core was inspected visually for abnormalities such as the inclusion of large stones, severed mole channels or undesirable cracks resulting from transportation. All acceptable cores were trimmed to a length corresponding to at least 1 inch less than the shortest sample in the group. This eliminated any compaction in the lower few inches of the cores, resulting from pressure from the screwdriver handle during the extraction of the inner tube and core from the boring apparatus.

(d) Waxing Techniques

(i) Initial Techniques

One half of the rigid semi-cylindrical containers surrounding the core was removed, and glossy paper, or a plastic sheet, placed over the core. That half of the container was then replaced, with the plastic sheet between it and the core. Holding both containers together, the whole was inverted and the other half of the container removed, leaving the core exposed and bedded in the plastic sheet and concave of the first container half. Molten paraffin wax was then applied with a $1 - 2\frac{1}{2}$ inch paint brush to the exposed half of the soil core. After several coats of wax had been brushed on, the whole was allowed to cool. The half container that had been removed was then cut with a hand cross-cut woodsaw to a length corresponding to about 2 inches shorter than that of the core. This shortened half container was then dipped in a trough of molten wax, to seal it against water uptake. On cooling, it was placed over the waxed portion of the core so that an inch of core protruded from each end (one inch was about the maximum length of core that could be safely unsupported by the mould). Again holding both container halves together, the whole was inverted and the upper half removed. The plastic sheet, or glossy paper, acted as a shield so that wax, running down in the initial painting, did not adhere to the container half. If this condition was not avoided, removal of the half container was invariably accompanied by removal of pieces of the core sealed to the container by the paraffin wax.

The plastic, or glossy paper sheet was then peeled carefully from the excess wax, leaving the other largely unwaxed half of the core exposed so that it could be brush coated too. Up to this stage, the waxing technique proved entirely satisfactory for all cores in all conditions. However, the technique initially incorporated, for sealing the core to its support, subsequently proved unsatisfactory. The technique consisted of binding the waxed core into the half container it rested in during the coating of the second side. Transparent adhesive tape was used for this purpose. The uppermost ~~half~~ of a reagent bottle was then waxed onto the upper end of the core (Plate XX), and a disc of zinc gauze to the lower end. Cotton wool was used as the reinforcing agent and filler for any large gaps between the bottle top and the core.

The limitations of this technique were that leaks in the wax sheath, which invariably developed, could not be easily resealed, especially if they occurred in that portion of the sheath resting in the half container. Additionally, the wax - glass seal was often inadequate and could not be easily rectified once a water film existed between the wax and glass surfaces.

PLATE XX

The upper portion of a reagent bottle (with supply line attached) sealed to the core

(ii) A Satisfactory Waxing Technique

After the initial brush coating of paraffin wax, as described above, bottle tops were waxed in place on both the top and the bottom of the core. To improve the glass - wax adhesion, the half bottles were sandblasted to give a rough external surface. Again cotton wool was used as a reinforcing agent to improve the sealing properties and strength of the wax. When the wax had solidified and cooled, rubber bungs were temporarily inserted in the bottle tops. Each bung had a glass tube passing through it and bending upwards for 3 or 4 inches, to prevent internal pressurization of the core through temperature changes during waxing. The whole core, with glass bottle tops attached, and supported in the half container, was then dipped briefly in a long trough of molten wax and allowed to cool, suspended by supports passing right under the half container. The reasons that each core was brush coated before dipping, were; (1) so that penetration of molten wax into the core would be minimized, and (2) so that the bottle tops could be pre-attached and sealed, to prevent wax from coating the infiltrating or effluent surfaces of the soil. Each core was eventually dipped six to eight times in the trough, care being taken to allow successive coats of the paraffin wax to solidify and cool before applying the next. In this way, the core was sealed into the half container and the wax sheath passed entirely over the half container, core, and bottle tops, thus affording a maximum seal and water proofing. After a substantial coating of wax was built up, the bungs were removed from the bottle tops and the core was ready for percolation or permeability trials.

Contrary to the recommendations of Slater and Byers (1931), it was found that with the technique described above, the temperature of the molten wax was not critical within fairly wide limits. However, if the cores had been coated in a very dry state, perhaps the rate of solidification of the paraffin wax might then have become most important. The wax used was a commercial product, "Wolfe's Preserving Wax" *, and provided the temperature of the molten product remained between 75 and 110° C, no difficulty was experienced in its application to the coating of cores.

It should be noted, however, that below 75°C, the molten wax set too rapidly on contacting the core and did not seal to the peripheral particles adequately. This was most pronouned when brushing on the wax. Above 110°C, the wax tended to soak into the core, especially if the latter was a little dry. Use of wax above this temperature was, therefore, not recommended. Above about 140°, the wax would boil and become discoloured, and there was a distinct danger of ignition.

Several techniques of cutting the reagent bottles in half were investigated, including the use of a hot iron rod in vegetable oil contained within the bottle, as briefly described by Jackson (1958), and hot wire and twine techniques. Eventually, a satisfactory technique of leading a crack around the bottle by repeated applications of a glowing hot glass rod was used.

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* "A pure refined wax" packed by Crocombe and Russell Ltd., Auckland.

(e) The Positioning and Sealing of Piezometer Tubes on to the Cores

(i) Initial Techniques

In order to study pressure head differentials throughout the profile, at certain points small holes were chipped in the wax sheath and glass tubes waxed in place in such a manner that the right angle bend in the lower end protruded up to $\frac{1}{2}$ inch into the soil, while the body of the tube was strapped to the core, and ran up to the soil surface.

Limitations of studying pressure differentials, with the cores held in a vertical position, will be discussed later. However, certain limitations of the technique of fixing the piezometer tubes to the cores also existed. For one, even with the use of a cotton wool reinforcing agent, the glass - wax seal was again inadequate, and sandblasting the tubes was impractical as their transparency was essential to their function. Additionally, soil often became firmly wedged in the open tube end protruding into the profile, and this seriously affected the sensitivity of a tube in indicating pressure changes as a function of time. On the other hand, occasionally, small earthworms took the opportunity to move into these ready made channels. This, of course, added further obstructions. About the same time as it was realized that this sealing technique was inadequate, it was decided to conduct subsequent experiments with the cores held in a horizontal position.

(ii) A Satisfactory Technique for the Sealing of Piezometer tubes on to the Cores

After the first one or two coats of paraffin wax, from dipping in the long trough, holes were made in the sheath by gently inserting a warmed # 6 cork borer at points corresponding to 3, 6, 9, 12, 15, 18, 21 and 24 inches below the surface of the profile. Approximately $\frac{1}{8}$ inch of soil was removed from the core periphery as well. In earlier trials, insertions were made at 3, 6, 9, 12, 18 and 24 inches. Into each hole was pressed a $\frac{3}{8}$ inch diameter disc of fine brass gauze. Eight 12 inch lengths of $\frac{5}{32}$ inch bore glass tube were clamped in vertical positions so that each of their bases rested on the gauze disc in each hole. Into the gauze-bottomed holes, and around the bases of the glass tubes positioned in the holes, were pressed small quantities of cotton wool to prevent stray sealing material from blocking the ends of the glass piezometer tubes during the sealing process. The base of each tube was then sealed to the wax with a plastic fibreglass compound*, the material being spread

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*Plastibond, a commercial plastic fibreglass compound, manufactured by N.P. Croft & Co. Ltd. Lower Hutt for approximately a 1 inch diameter footing around the tube and hole cut in the wax sheath, (Fig. XIX). The seal between the fibreglass and the wax was not, itself, ideal due to the greasy nature of the surface of the wax, but the seal to the glass by the fibreglass was complete and lasting. After a suitable hardening time for the fibreglass (from 20 minutes to 3 hours, depending on the temperature, and the quantity of catalyst used), the clamps were removed from the glass tubes. Cores, bottle tops, half containers and the bases of the glass tubes were then dipped a further five or six times in the trough of molten paraffin wax, making sure that at each dipping, the wax covered the fibreglass footing around the base of all tubes. After the final coat had solidified and cooled, 1 inch graduations were marked on the piezometer tubes with a felt pen.

(f) Laboratory Mounting

When percolation trials were undertaken, the cores were mounted by simply clamping the half container supports to retort stands, screwed to the bench. However, when permeability trials were undertaken, with cores in a horizontal position, a special hinged table was utilized. Cores were mounted on the table in a horizontal position with a combination of screw clamps and wire supports. When connecting the water supply line, in order that the surface of the soil would remain uniformly wet, with the avoidance of an air bubble accumulating in the bottle top, it was desirable that the bottle tops should be pre-filled with water with the cores in a near vertical plane.

Plate XXI shows six cores mounted on the table, with the latter in a near vertical position, ready for pre-filling of the bottle tops.

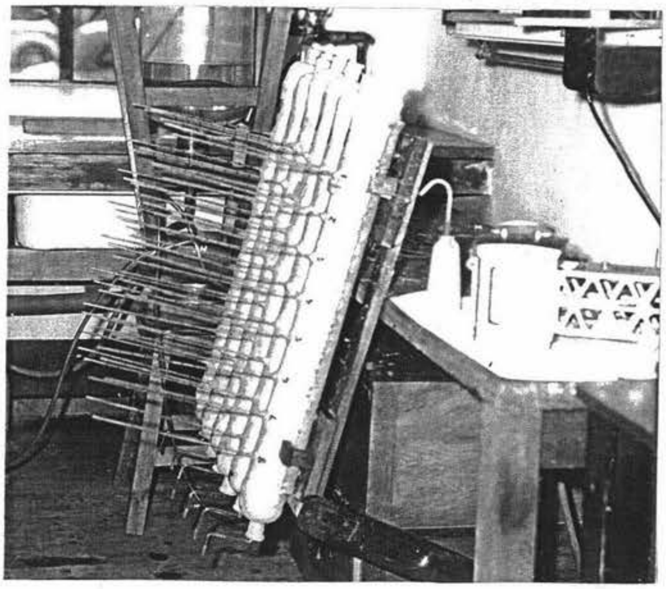

PLATE XXI

The hinged table (supporting six cores) in the near vertical position

Plate XXII shows the same six cores, with the table in the horizontal position, the bottle tops charged, the supply line connected, and the U.V. light shield fitted. It was in this position that the pressure differentials throughout the profile were indicated by the piezometer tubes shown.

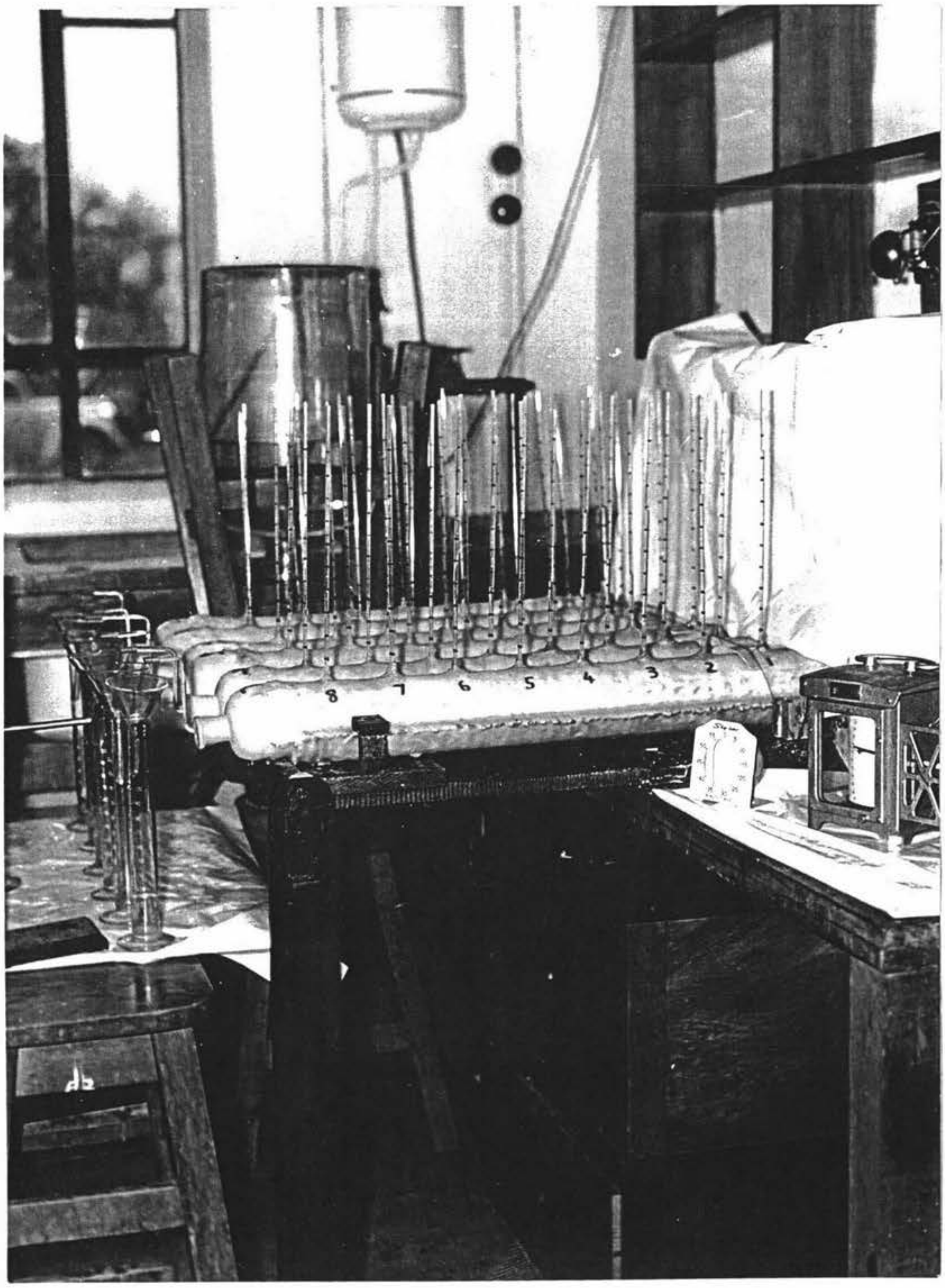

PLATE XXII

inged table (supporting six cores) in the horizontal position during a permeability experiment

(g) Repairs and Maintenance

Normally, if a core developed a leak, such a core had to be removed from the system and the hole resealed with molten wax at about 110°C, or hotter. However, if the leak was a slow one, often a preliminary seal could be accomplished by gently playing a small bunsen flame on and around the area, and then brushing on liquid wax, without disconnecting the core from the permeability experimental system. This latter technique was often aided by applying cotton wool over the hole to act as a reinforcing agent.

Leaks developing around the bases of piezometer tubes could be dealt with in situ. A fine bore glass tube, attached by rubber tubing to a vacuum pump, was slipped down the piezometer tube so that its lower end rested on the gauze (or, in the case of vertical cores, on the inside of the bend) at the bottom of the tube. With a constant vacuum maintained, all water in the piezometer tube was removed. No vacuum was applied to the core itself, as the space between the fine bore glass tube and the piezometer tube was sufficient to allow air intake. By this means, the leak would stop as there was no head of water present in the tube. The hole could then be resealed with hot paraffin wax and cotton wool reinforcing. It was essential that the vacuum be maintained until the patching had solidified and cooled (10 - 15 minutes), so that water pressure was again permitted only when the wax was stable enough to withstand it.

If many and reoccurring leaks persisted, it was usually a sign that insufficient wax had been applied to the core to withstand the pressure maintained by the constant head reservoir. In this situation, all the cores were disconnected and re-dipped, two or three times, to increase the strength of the wax sheath surrounding them.

In the advent of the seal between the sandblasted glass and the wax sheath being inadequate, cotton wool was wrapped around the rubber bungs, with their glass tubes protruding, and waxed so that the sheath then included the bung. As a rubber - wax seal was more effective than a glass - wax seal, increasing the wax sheath to encase also the rubber bungs at each end of the core served to overcome most leaks developing in these regions.

III SUPPLEMENTARY LABORATORY EQUIPMENT AND TECHNIQUES ASSOCIATED WITH HYDRAULIC STUDIES OF THE "UNDISTURBED" SOIL CORES

(a) Infiltrating Water Supply

The techniques described by Slater and Byers (1931), Fireman (1944), Marsh and Swarner (1948), Bower and Petersen (1950), Steinbrenner (1950), Bloodworth and Cowley (1951), and Taylor and Heuser (1953) were critically examined in relation to maintaining a constant pressure head water supply to the cores.

(i) Percolation

With percolation studies, it was felt that in agreement with Slater and Byers (1931), Fireman (1944) and Swartzendruber (1962), it would be desirable to keep the hydraulic gradient, 'i' , to as near unity as possible in order to simplify subsequent calculations and to avoid any surface head - flow rate relationships, which seemed to be a controversial consideration of many investigators. To achieve this, a technique was developed that eliminated the surface head entirely.

As shown in Figure V, with the half bottle sealed to the top of the core, an air-tight system was formed. Working on the syphon principle, water was delivered at zero surface head to the core surface. As water moved down through the profile, a pressure differential was set up between the core surface and the reservoir surface, with a consequent flow of water to the core. Provided always that the supplying conduit system remained free of air, the system was both efficient and effective and completely eliminated the hydraulic gradient expression, 'i' , from the Darcy equation. To check that air bubbles had been excluded from the system, glass 'T' junctions were used to supply each core (six of which were usually connected in series), and $\frac{3}{16}$ inch i.d. clear plastic tubing was used to connect all the 'T' junctions with the supply reservoir. Plate XX shows a glass 'T' hermetically sealed into the glass top affixed to the core. The procedure of initiating a percolation run, utilizing this system, was as follows:-

(1) All six cores were mounted vertically and their heights in the clamps adjusted until the soil surfaces, carrying the vegetation, were all level (to within $\frac{1}{4}$ inch) with the surface of the constant head reservoir.

(2) The overflow pipe outlet from the reservoir was clamped, and the reservoir level allowed to rise to approximately 4 - 6 inches higher in elevation than the tops of the bottle halves. At this stage, the clear

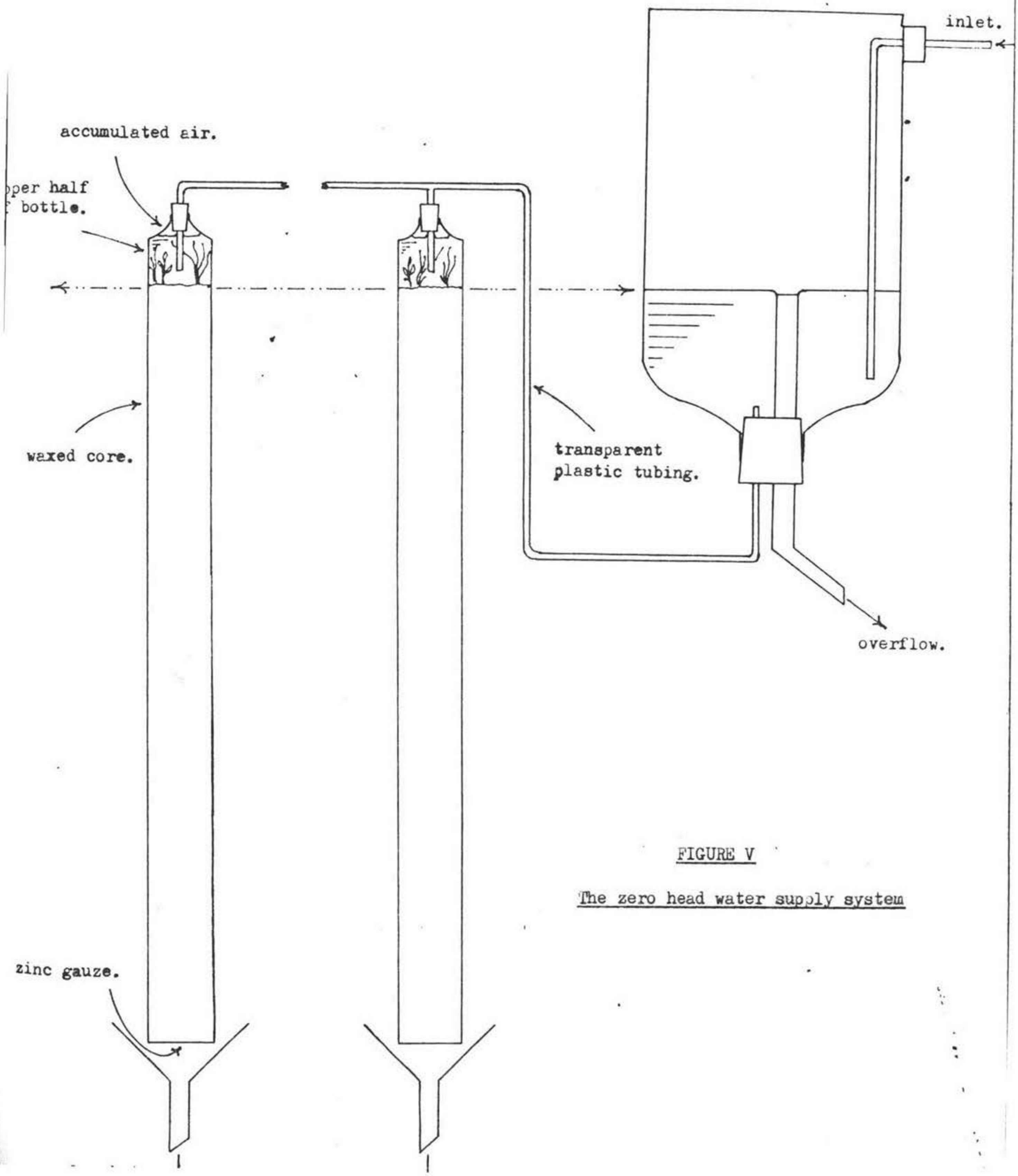

FIGURE V

The zero head water supply system

plastic supply line was also clamped.

(3) All glass tops to the cores were carefully pre-filled with water from a beaker or wash bottle. Immediately all were full, the transparent supply line from the reservoir was unclamped and the rubber bungs, through which the 'T' junctions passed, were pressed into the bottle tops on the cores, making sure all air was excluded.

(4) To minimize the time under which the core tops and glass - wax seals were subjected to up to 8 or 9 inches head of water, immediately the last connection was sealed into the glass top, the reservoir overflow was unclamped and the level allowed to return to its original state. As this state was approached, so too did the surface head on the cores approach zero.

(5) All cores were dried externally and a close watch was kept, as the wetting front descended, to observe and deal with any leaks that developed in the wax sheaths surrounding the cores. Frequently, water could be observed leaking around the glass - wax "seal" when the system was being charged. This arose from the 8 to 9 inch head of water necessary to charge the system, and was of little consequence because when the head was again reduced to zero, such leaks invariably ceased. In fact, that portion of the system that leaked under a positive pressure of 8 to 9 inches of water, then formed part of the system which was subjected to slight negative pressures as the wetting front moved down the profile. Under zero head conditions, a small quantity of air was often admitted through this glass - wax "seal". To avoid such air admittance from disrupting the syphon system, it will have been noticed in Plate XX and Figure V that the stem of the glass 'T' junction passing through the rubber bung, projected downwards for approximately 2 inches into the interior of the bottle top. This allowed air entering the system from the glass - wax "seal", or gases displaced from the soil during percolation, to become trapped in the glass top without disrupting the syphon system. It was a very infrequent occurrence for sufficient air and gases to be trapped to create a gas space large enough to extend down to the terminal end of the glass 'T' stem. If, however, this did occur, restoration of the system for that particular core took one of two possible courses. In the event of the gas bubble having extended into the clear plastic supply line, the only remedy was to disconnect all cores and recharge them as before, after attempting to locate and

eliminate the source of air intake into the system. Eliminating the source itself, often proved to be difficult, especially if it was a direct result of gaseous displacement from the core. This, of course, strengthened the case for the use of cores at a moisture content as close to "saturation" as possible. However, if the gas bubble, though large, was still confined to the bottle top alone, clamping the plastic supply line on either side of the 'T' junction enabled the bung to be safely lifted, the bottle refilled, and the bung replaced. It was essential to minimize the time taken to accomplish this, because:-

a. Temporary termination of the water supply to cores beyond the one in question, if prolonged, caused excessive gaseous rise from those cores, due to the negative pressure built up in the overlying surface water as the wetting front and transmitting zone moved down, with no replenishment from above.

b. Removal of the bung from the core in question, immediately resubjected that particular core to a positive pressure in the region of 2 to 3 inches of water and, as described above, this was undesirable except for short periods of time.

The system and apparatus described above was also utilized, essentially unchanged, with the stratified sand column percolation trials (to be described later).

(ii) Hydraulic Conductivity Experiments Utilizing a Constant Head Supply Reservoir

For the hydraulic study of soil cores maintained in a horizontal position, essentially the same water supply apparatus, which has been described above, was used. The only modification of the method was that the surface level of the reservoir was maintained at a predetermined elevation above the infiltrating surfaces of the horizontal cores. To eliminate the hydraulic gradient expression, 'i', from the Darcy equation, when testing 30 inch cores, ideally the difference in elevation should have been 30 inches. However, such a pressure at the intake end of the cores would have been excessive in relation to the strength of the wax sheaths. For several minor reasons, but not with complete disregard for simplification of the 'i' expression, a constant static head of 9.5 inches of water was maintained in the common supply line.

The procedure for the charging of a battery of six horizontal cores was:-

(1) With the cores mounted side by side on the special swivel table, the latter was swivelled so that all cores adopted a near vertical position (Plate XXI).

(2) The overflow outlet of the reservoir was clamped, and the reservoir allowed to fill to a level corresponding to a surface elevation 4 to 6 inches above the bottle tops on the cores.

(3) The bottle tops were filled, as before, from a beaker or wash bottle, and the bungs, carrying the glass 'T' junctions and clear plastic supply line, inserted.

(4) The reservoir overflow was unclamped and the surface level allowed to revert to its original position. It was essential that this was accomplished <u>before</u> rotating the table to the horizontal position to avoid subjecting the cores momentarily to excessive pressure head.

(5) With the reservoir level back to normal, the table was re-swivelled to the horizontal position (Plate XXII), thus bringing a 9.5 inch head of water to bear on the soil surfaces.

The exclusion of air bubbles in this system was not of such paramount importance as with the zero head percolation system. However, the reason for charging the bottle tops with the cores in a vertical position, was that the large air bubbles, which would have been present in the bottles if they had been charged in the horizontal position, were avoided. For this reason, it was desirable also to largely avoid the entry of air into the system during the experiment. Again, displacement of gases from the porous system accounted for a portion of any accumulated bubbles, but unless successive, they were unavoidable and of little consequence. In fact, much of the soil air was displaced through the piezometer tubes as the wetting front moved through the profile.

(b) <u>Flow Rate Recording Apparatus and Techniques</u>

In all cases, the leachate from cores was collected in measuring cylinders, or where the volume was excessive, in up to 10 litre flasks or similar containers. Where any particular core showed a marked increase in flow rate, especially if this resulted in a computed hydraulic conductivity well in excess of 10 inches per hour, such a core was disconnected from the system. The 'T' junction serving that core was sealed to avoid failure of the system serving the remaining cores. Any such core disconnected was then allowed to air dry and was visually examined in detail. Almost invariably, examination revealed longitudinal, or at least diagonal, cracks or channels having developed. These channels were usually capable of transmitting water at a relatively high rate of conductance. Similarly, cases were identified where the increased or excessive flow rate appeared to be attributable, at least in part, to lifting of the wax sheath from the core periphery, thus allowing channelling between these two bodies.

Fireman (1944) claimed to have found no apparent advantage in pre-displacement of air from cores by enforcing upward rise of the wetting front. Wyckoff and Botset (1936) and Childs and Collis-George (1950) also cast doubt on the advantages of substituting a more readily soluble gas (e.g. CO_2) for the air. Consequently, no pre-displacement or replacement of gases within the porous system was undertaken with any of the experiments conducted by the author.

With the horizontal cores, a technique was developed which was designed to obviate the possibility of horizons, that underlay the least permeable horizon, not becoming "saturated". Rubber bungs were inserted in the glass bottle tops at the effluent ends of the cores. Through each of these bungs passed glass tubes, which on the outside were bent upwards and then horizontally so that the leachate was ejected from the ends $1\frac{3}{4}$ inches above the level of the topside of the cores. On the inside of each of the bottle tops, the glass tubes were bent upwards at an angle of about 30° to the vertical, and their lengths were adjusted so that they terminated just clear of the highest internal point in the bottles when the latter were in the horizontal position. This ensured, then, that the effluent bottle tops would be practically fully charged before any leachate was ejected externally from the glass tubes.

It did, however, require up to 150 mls. to charge each of the half bottles. Consequently, no flow from the tubes would be registered until this volume of water had passed out the bottom of each of the cores - and this could have taken up to 15 hours. Thus, early fluctuations in flow rates would not have been recorded, and indeed, no flow rates at all would have been recorded for some time. To obtain early flow rate recordings before anaerobic microbiological activity in the cores became a dominant factor, the effluent bottle tops were charged in the following manner:-

(i) With the bungs and associated glass tubes inserted, a fine glass rod was heated in a bunsen flame to just below its plasticity point.

(ii) The hot rod was pushed gently through the top of the wax sheath of each core in turn at about a 45^0 angle, so that it passed by the cut end of the bottle top embedded in the sheath, and finally protruded into the interior of the bottle top at about the top of the enclosed cavity.

(iii) An identical rod, but cold, was pushed through the small hole a few seconds after withdrawl of the hot rod, to clear the hole of melted wax, enough to transmit air.

(iv) A wash bottle with rubber hosing was connected to the ejection end of the glass tube passing through the rubber bung.

(v) Water was forced into the bottle top cavity from the wash bottle, the air being displaced through the small hole in the wax.

(vi) When water began to emerge from the wax hole, it was indicative that the cavity had become filled with water.

(vii) The wash bottle was disconnected, spillage water dried from around the wax hole and cotton wool and hot paraffin wax was applied to the small hole to reseal it. Any water flowing from the core was then almost immediately ejected from the glass tube.

(viii) This technique was quite simple to apply, although it is stressed that it was administered as soon as possible after initiation of a permeability run. This was to ensure that little, or no water from the core was flowing into the bottle top cavity during the operation. Should water be flowing, its presence could make resealing of the small wax hole difficult to achieve, as water would be continually attempting to find its way out by this passage.

As mentioned previously, the desirability of maintaining all horizons in a "saturated" state during hydraulic studies of the soil was the main reason underlying the change from mounting cores vertically to mounting them in a horizontal position with a head of water at both the inlet and outlet ends. The result was a total pressure differential throughout the length of the cores of 7.75 inches of water, as opposed to 30 inches when mounted vertically.

In the first period of permeability runs, while the wetting front moved through the profile, readings of flow rate (if any) and pressure distribution were taken hourly. After a reasonably steady flow rate had been attained, readings were reduced to two per day.

The time interval for a pre-determined rise in water level in the piezometer tubes could also be recorded. The effluents of the horizontal cores were first sealed off. To eliminate interference to readings from pressure heads in adjacent tubes in a particular core, all tubes except the one being tested were also temporarily sealed. The water level in each tube tested in turn was reduced to 1 inch, by drawing the excess off with the vacuum device described previously under "Repairs and Maintenance". It was hoped that the time rate of rise to the 2 inch graduation would then give an indication of the conductance capacity of the soil down to this depth. In the less permeable soils, especially with a high percentage of clay, the time rate of ascent of the water level could be extremely slow. Hence, an electrical relay was incorporated. Two fine copper wires were pushed down the tube to the 2 inch level, after the water level had been reduced to 1 inch, and a stop-watch started. The bared ends of the wires had been pre-dipped in concentrated NaOH solution. When the water level eventually ascended to 2 inches, it contacted the bared ends of the wires, with the result that the NaOH dissolved off the wires and momentarily formed a highly ionized electrolyte in their immediate vicinity. The result was the closing of an electrical circuit, which, with a 90 volt battery incorporated, initiated the ringing of a bell.

A continuous record of the air temperature fluctuations in the laboratory was kept with a thermograph.

(c) Laboratory Temperature Control

Although it was considered that internal temperature variations of the soil cores would be heavily damped due to the mass of the soil bodies and their low specific heats, it was considered also that the temperature of the water in the supply lines, in taking approximately 2 hours to move from the reservoir to the cores, would be governed largely by room air temperature. As seen from the control trial, which is described later, the changes in the viscosity of water over the temperature range experienced, was sufficient to significantly affect the flow rate through the porous system. In light of these findings, and in general agreement with those of Fireman (1944) and Miller and Gardner (1962), all subsequent hydraulic trials were conducted in a thermostatically controlled room at a temperature varying by a maximum of 4°F. Thermographical records were kept to maintain a constant check on the functioning of the thermostat mechanism.

(d) Distilling Apparatus

For the investigation of the relative effects of distilled and tap waters as the permeating liquids, a distilling plant was set up utilizing three glass condensers and a steam supply from a 10 litre flask heated by a gas burner. The hot, distilled water was led in clear plastic tubing to a standard commercial refrigerator. Several turns around the ice box were sufficient to cool the water to approximately room temperature, the final adjustment being facilitated by the 8 ft. length of plastic tubing exposed to air temperature on its way from the refrigerator to the reservoir. The flow of distilled water was sufficient to allow some overflow from the reservoir, as well as supply the demands of the six cores.

During the evening, a drip feed from a 10 litre flask was substituted for the direct distillation apparatus, the drip feed rate being maintained slightly in excess of the total demands of the cores.

(e) Soil Core Microbiological Analysis and Sterilization Techniques

With prolonged saturation, some cores showed a marked drop off in flow rate with time (in agreement with Allison 1947, and McCalla 1950). This was found to be often attributable, in part at least, to decay and putrification of the surface vegetation, and associated blocking of pores with microbial residues. The odour from the core surfaces at the termination of a trial indicated anaerobic activity, and further investigation appeared to be desirable. Using the Azatobacter Plaque technique (Winogradski 1926), with soil only as the medium, microbial colonies were found to be present on the surface of the soil, but it was considered that the technique had not yielded significant results. Through pressure of time, no further effort was made to objectively establish the presence of anaerobic activity in the soil surface layers or throughout the profile, though no doubt, such a study would have been beneficial.

Under certain conditions, some sterilization of the soil was considered desirable. For vertical cores, 100 mls. of 1:500 mercuric chloride was introduced into the top of each core bottle. With horizontal trials, however, an extra 'T' junction was introduced into the supply line, with a clear plastic tube leading from it and terminating, open, at a level above the static head of the reservoir. Through the open end of this tube, 2 grm. mercuric chloride pills were introduced. They eventually lay in the supply line, and in dissolving slowly, produced a constant supply of liquid $HgCl_2$ to the core tops. Judging by the colour of the solution, the supply was most probably in the order of 1:500 to 1:3000 concentration. The leachate from each core was tested thereafter to determine when $HgCl_2$ had passed through the cores. When all cores exhibited a positive test (conducted by addition of 8% thiocetamide to a sample of the leachate), the supply of the bactericide was terminated.

(f) Suppression of Earthworm Activity in Soil Cores

Especially with cores supported in a vertical position, surface damage by earthworm activity could be most pronounced and detrimental. With prolonged saturation, the organisms were driven to the surface, where they emerged. With up to 4 or 5 worms per core confined to the 6 square inch surface of each core, their continual activity had the effect of disturbing, and eventually partially sealing the infiltrating soil surface. Additionally, their eventual death greatly assisted the build up of putrifactive bacteria and fungi.

The problem of dealing with the earthworms became quite complex when it was considered that:-

(i) Any method employed to drive them from the soil prior to the experiments was of questionable value, as a soil with worm channels not partially blocked by the living organisms, could have exhibited a greater conductance value than one where the organisms remained in their natural habitat.

(ii) The use of chemical deterrents of earthworm activity ran a great risk of interferring with the exchange complex of the soil, which is essential to hydraulic conductivity.

(iii) Mercuric chloride, introduced to the inlet bottle tops when earthworms were visually detected on the surface, caused such frenzied activity of the organisms before they eventually died, that the total surface damage caused by them was, if anything, increased. For this reason, introduction of $HgCl_2$, even as a soil sterilent, was restricted to situations where its presence was essential to the continued function of the porous system.

(iv) Killing of the organisms while still within the soil, might have greatly increased the incidence of pore blocking by putrifactive microorganisms.

Attemps to drive earthworms from the soil by application of an electrical potential difference across portions of the core proved to be only partially effective. With a p.d. of up to 500 volts, a.c. applied, the response was varied. While in some cases earthworms appeared on the surface in a relatively short period of time, other cores subjected to the treatment produced no organisms except a few millipedes. Dissection of the latter cores often revealed live earthworms apparently unperturbed by the 500 volt potential difference. Additionally, even with alternating current, the risk of electrolytic disturbances in the soil fluids, could not be ignored.

The most successful technique adopted in dealing with these organisms was with the use of ultra violet light. A 3 ft. U.V. tube-lamp was set up over the core bottle tops, direct radiation being shielded from the eyes of observers (Plate XXII). The bottle tops, being of soda-glass, greatly reduced the intensity of the U.V. rays in the water overlying the soil surface. However, in most cases it served as a sufficiently unpleasant deterrent to worms to confine them to the soil. Even after 2 weeks continual "saturation", it was found that earthworms confined in this manner to the soil body were able to survive. It was considered that such conditions were the most ideal that could be achieved in the circumstances of prolonged "saturated" flow studies of "undisturbed" soil profile cores.

(g) Examination of Soil Cores for Irregularities

Taking into consideration the criteria for core rejection discussed by Slater and Byers (1931), it became necessary to visually examine any cores whose composition was suspect as a result of atypical flow rate and pressure head recordings. Slater and Byers (loc.cit.), amongst other reasons, rejected cores without consideration to permeability values when visual examination alone revealed cracks and channels which might have indicated an atypical core. It is the author's opinion that such a single criterium as a basis for rejection, is subjective in excess. It was considered more objective if flow rate recordings and visual examinations were considered together in the culling of cores. Only where a permeability value was noted to be excessive, in relation to other cores of the same soil type, was the core carefully dissected and visually examined for abnormalities. Where there were cracks or large channels present, or where the wax sheath could be seen to have lost intimate contact with any part of the core periphery, that core was then rejected, as those undesirable features could readily have contributed to the excessive 'k' value.

(h) Examination of Certain Physical Characteristics of Soil Cores

When extracting cores G_2, H_2, I_2, J_2, K_2 and L_2, an extra core was obtained from the same sampling area. This core was not waxed or in any way directly tested for hydraulic conductivity. Instead, certain of its physical characteristics were studied in the laboratory to provide a profile description and a guide to the expected intrinsic permeability of the profile.

(i) Profile Description

The basic field techniques of Clarke (1957) were employed in the laboratory in describing the physical characteristics of the profile. The characteristics of each horizon considered were; colour (Munsel description), texture (subjective analysis), consistency (subjective analysis), moisture condition, visible porosity, and structural classification.

Several tests, complementary to the profile description, were performed also.

(ii) Examination of Compaction within the Profile

For this purpose, a small spring penetrometer was utilized. In order to avoid the variations caused by differential moisture contents in the successive horizons, the core utilized for the subjective profile description was allowed to partially air dry in the laboratory. Hence, when the penetrometer was applied, all layers of the core could be assumed to be at approximately equal moisture contents. The penetrometer needle was pushed into the core at three places at each of the depths corresponding to the arbitrary 3 and 5 inch layers of the waxed samples.

(iii) Structural Examination

Following the recommendations of O'Neal (1949), the soil core utilized for the subjective profile description was carefully broken in several planes in order to gain an appreciation of the direction of easiest natural fracture. Structural units identified were also further examined to ascertain the degree of overlap and the ratio of vertical to horizontal axes.

(iv) Mechanical Analysis

Adopting an accepted laboratory technique, replicate mechanical analyses were performed on two other cores extracted from an area in close proximity to that from which cores G_2, H_2, I_2, J_2, K_2, L_2 and the "profile description core" were extracted.

IV LABORATORY HYDRAULIC STUDIES OF AN ARTIFICIALLY PACKED SAND COLUMN

(a) The Equipment

To subject a profile of known composition to identical conditions to those of soil cores being tested, an artificially packed sand column was set up. To the base of a 36 inch length of $2\frac{3}{4}$ inch i.d. seamless clear perspex tubing, was attached a grate of perspex plate supporting a disc of fine mesh brass gauze. Holes were drilled at points 6, 12, 18, 24 and 27 inches up from the base. By arranging the surface of the profile to be 6 inches below the tube top, such points corresponded to 3, 6, 12, 18 and 24 inch depths in the profile. Through each hole was fitted a $\frac{3}{16}$ inch bore glass tube. The glass tubes protruded $\frac{1}{4}$ inch into the interior of the perspex tube, and on the outside they turned through 90° to run vertically to the top of the tube. All joints of glass to perspex were sealed with "Plastibond", and all perspex to perspex joints with "Araldite"* glue.

In operation, the perspex column was held vertically in retort clamps screwed to the bench, and the elevation of the profile surface was adjusted to correspond with that of the reservoir water surface. A $3\frac{1}{8}$ inch rubber bung was used to seal the zero head system supply line to the top of the perspex tube.

Plate XXIII shows the column during a percolation experiment.

(b) The Packing Procedure

Washed river sand was screened to four fractions. Those particles failing to pass a 2 mm. square mesh sieve were discarded. Those remaining particles failing to pass a 1 mm. square mesh sieve were retained as the coarse sand fraction. Those remaining particles passing a 1 mm., but being retained by a 0.5 mm. square mesh sieve, were retained as the medium sand fraction. Those remaining particles passing all sieves, down to and including 0.5 mm. square mesh were retained as the fine sand fraction.

The respective sand fractions were poured, oven dry, through a funnel into the column in the order of fine, coarse, medium. Sufficient of each grade was added to result in approximately equal depths of all grades. In practice, however, after tamping, the profile consisted of an upper 11 inch horizon of medium grade sand,

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* A commercial glue manufactured by Aero Research Ltd., Cambridge, England.

a 'B' horizon of 9 inches of coarse grade sand, overlying a 'C' horizon of 10 inches of fine grade sand. The only factor governing which grade of sand should comprise which horizon was that the fine sand should make up the 'C' horizon, to ensure that all horizons would become "saturated" during percolation experiments. This was based on the reasonable assumption that the least permeable horizon would, in fact, be represented by the fine sand fraction.

To compact all horizons, the column with the freshly poured sand, was dropped several times through 6 - 9 inches, base first, on to a cloth padded chair. The inertia, causing compaction, would of course be greater in the deeper horizons, but this was not seen as a disadvantage of paramount importance in this case, where production of standard conditions was not being attempted.

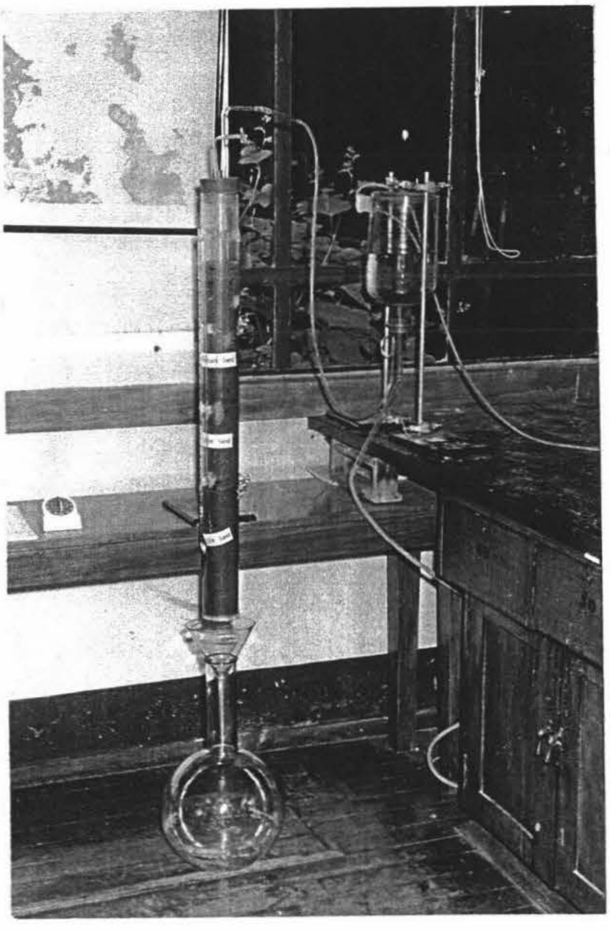


PLATE XXIII

The Sand Column and an overflow reservoir during a percolation experiment

(c) Infiltrating Water Supply and Recording Techniques

An identical overflow reservoir system to that used with soil cores, was utilized, and the procedure for charging and initiating a percolation run was identical to that described for the waxed soil cores held in a vertical position. However, due to the mechanical instability of sand profiles, the downward movement of the wetting front generally caused a quantity of sand to move into the bases of the top two or three glass piezometer tubes. This was easily rectified when the wetting front was observed to have passed further on down the profile. A fine bore glass tube, attached by rubber tubing to a water supply, was inserted in the top of each piezometer tube affected by migrating sand. As the tube was gently pushed down the piezometer tube, its water flow washed the sand particles up the space between it and the piezometer tube, and spilt them from the top of the latter. Care, however, was necessary when attempting to wash coarse sand particles out in this manner. Unless the fine bore tube was continually agitated vertically, there was a danger of particles becoming firmly wedged between the two tubes. When this occurred, generally the fine bore tube was eventually broken, leading to failure of that particular piezometer tube to accurately participate in the profile pressure differential recordings.

As with soil cores, flow rate recordings were taken at regular short intervals together with piezometer tube readings, until such time as the piezometer tubes did not vary greatly within one interval. Subsequent readings were usually taken at approximately 6 or 12 hourly intervals.

SECTION E

RESULTS AND DISCUSSIONS

The results of experiments, and pertinent discussions, will be considered under the following headings:-

I Distilled water and tap water as the infiltrating fluids.

II Examination of the flow rate from a capillary tube, as it was affected by diurnal air temperature fluctuations.

III Hydraulic tests on the stratified sand column.

IV Hydraulic tests on "undisturbed" soil cores from the Ongley Park profile.

V Hydraulic tests on "undisturbed" soil cores from the Ongley Park profile, with the flow direction reversed.

VI Measurement of the rate of rise of 'H' in individual piezometer tubes.

VII Indirect assessments of intrinsic permeability, based on laboratory examination of certain physical characteristics of "undisturbed" soil cores.

VIII A qualitative account of results obtained from previous hydraulic tests performed on soil cores from the Ongley Park profile.

I DISTILLED WATER AND TAP WATER AS THE INFILTRATING FLUIDS

From pilot trials, no outstanding difference was found between these two permeating liquids. Unfortunately, no data is now available to substantiate this finding, but in the light of the evidence compiled from these pilot trials, it was not considered to be of any great benefit to persist with the use of distilled water as the permeating liquid. Hence, all subsequent experiments were conducted utilizing the Massey University artesian tap water supply.

II EXAMINATION OF THE FLOW RATE FROM A CAPILLARY TUBE, AS IT WAS AFFECTED BY DIURNAL AIR TEMPERATURE FLUCTUATIONS

With cores tested in a vertical position, initial observations of flow rate as a function of time indicated that while the three phase flow rate - time curve proposed by Allison (1947) was adhered to in the long term, certain diurnal fluctuations in the short term were occurring. As the temperature fluctuation between 3 p.m. and 3 a.m. in July can be rather extreme, it was considered that a possible factor contributing to the variance of flow rate might be temperature. Presumably, the effect of any such temperature change would be distributed between a variation in viscosity of water, a variation in pore size, and biological effects. Which factor predominated was not determined. Fireman (1944) suggested that perhaps the dominant cause of permeability fluctuations with temperature was in the effect the temperature variations had on the viscosity of water. Viscosity decreases approximately $2\frac{1}{2}\%$ per centigrade degree rise in temperature. As the temperature fluctuation in the author's laboratory was up to 13°C during the period of the experiments, this would have represented a considerable viscosity variation. Fireman (loc.cit.) also noted that it had been shown that the relationship between the flow of water through soils, and viscosity, was not a direct one, presumably, he stated, because of soil - water interactions, which were affected by temperature changes.

It was decided, therefore, to investigate the possible effects of temperature fluctuations on the flow of water from a capillary tube. For this purpose, a glass tube was drawn out at one end to a fine capillary. This tube was connected to a constant head supply reservoir in an identical manner to that used with vertical cores and the sand column. Flow rate recordings were taken at the beginning and end of each day. The curve of flow rate (mls. per hour) as a function of time is given below in Figure VI(a), compiled from the data presented in Appendix IV. Also plotted in Figure VI(a) is the curve of the maximum and minimum temperatures experienced during the same period that the flow rate recordings were made.

The distinct similarity between the two curves indicates the effect that the diurnal temperature fluctuations had on the flow rate from the tube. Further verification of this trend is seen on studying the curves in Figure VI(b). For this experiment, the equipment was contained within a thermostatically controlled room (at 67 ± 2°F). The relative lack of flow rate fluctuations is clearly illustrated. On the basis of these

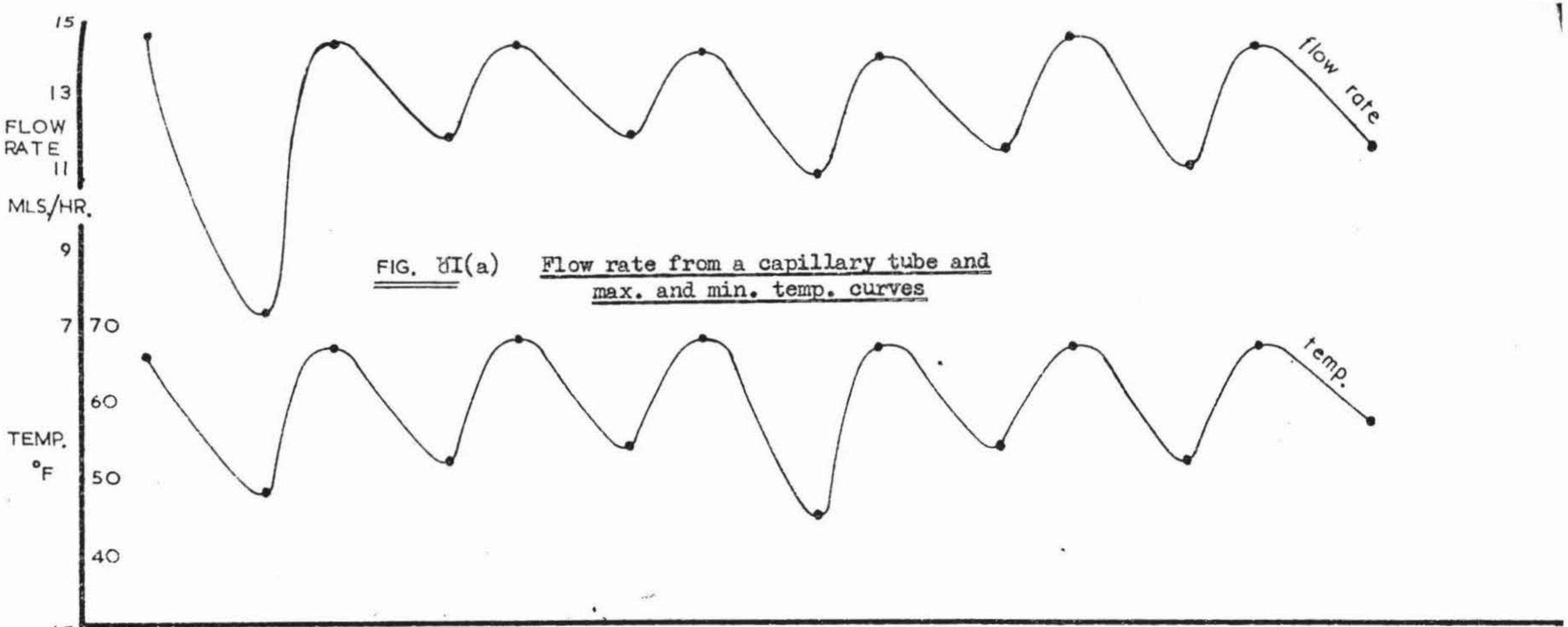


FIG. VI(a) Flow rate from a capillary tube and max. and min. temp. curves

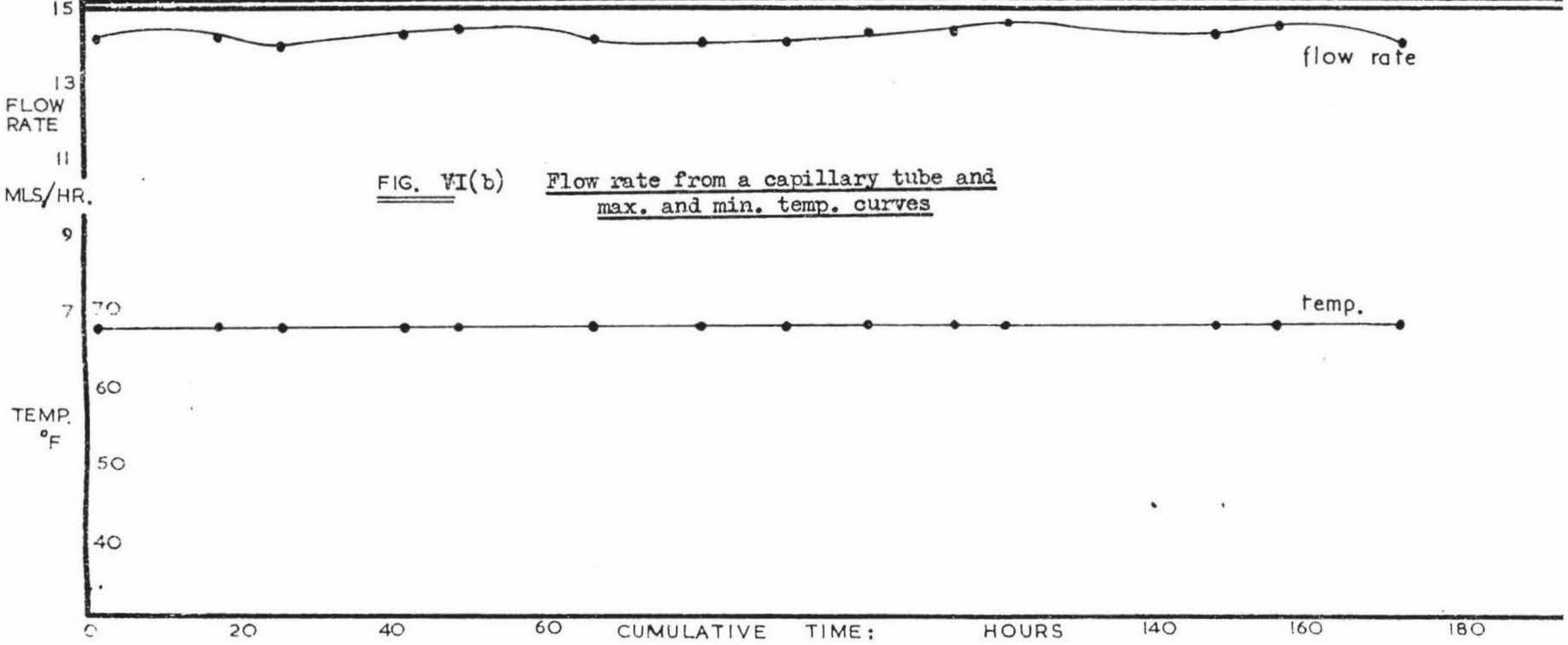


FIG. VI(b) Flow rate from a capillary tube and max. and min. temp. curves findings, together with the final recommendation of Fireman (loc.cit.) that consideration should be given to temperature effects when the maximum and minimum temperatures vary by more than 3.5°F, all subsequent flow rate experiments with soil cores or the sand column were carried out in the temperature controlled room.

III HYDRAULIC TESTS ON THE STRATIFIED SAND COLUMN

Specifications of the experimental conditions were as listed below:-

Dimensions of column	:	30 inches long, with an infiltrating surface area of 5.97 square inches
Percolating liquid	:	Tap water
Liquid supply	:	Overflow reservoir
Static surface head	:	Zero
Hydraulic head at core effluent	:	30 inches of water
Overall hydraulic gradient	:	Unity
Control of soil organisms	:	None necessary
Temperature	:	Controlled air temperature at 65 ± 4°F
Soil moisture content at initiation of experiment	:	Air dry
Nomenclature	:	The static head at a point in the profile is designated by 'h_s' followed by a subscript number indicating depth in inches. The hydraulic head at a point in the profile is designated by 'H' followed by a subscript number indicating depth in inches.

(a) Correlation of 'k' with Time

The hydraulic conductivity, 'k' , was computed directly from the flow rate, expressed in inches per hour, in the Darcy equation

$$v = ki$$

(where 'v' is the flow rate, and 'i' is the hydraulic gradient - in this case, unity). The flow rate, in inches per hour, was calculated from mls. per hour, utilizing the expression

$$\text{ins./hr.} = \frac{\text{mls./hr.}}{(2.54)^3 \times 5.97}$$

All pressure loss and hydraulic conductivity data for the duration of this experiment are presented in Appendix V.

In Figure VII(a), the curve of 'k' as a function of cumulative time, is shown for a total duration of $199\frac{1}{4}$ hours. For convenience of comparison of 'k' values with the family of curves in Figure VII(b), it will be noted that the ordinate in Figure VII(a) is labelled with numerical values increasing down the page. It was considered desirable to adopt this graphical procedure in preference to plotting the reciprocal of 'k' against time, as '$\frac{1}{k}$' was not a unit of universal recognition. Reversing the direction of the hydraulic conductivity ordinate allowed the universally acceptable 'k' to be plotted against cumulative time with the same abscissa values as the family of total pressure loss curves.

The main cause of the divergence of the curve in Figure VII(a) from the generalized curve described by Allison (1947) was probably attributable to the lack of colloidal material in the sand profile. The overall increase in 'k' with time (up to 150 hours) is considered to have been, at least in part, attributable to gradual dissolution of air trapped in the porous medium. With the progressive removal of air, an increasing total number of pores became available to transmit water. Entrapped air was readily observed in the profile through the transparent walls of the retainer. It was noticed during the experiment that obviously entrapped air gradually decreased in quantity with time. After 150 hours, it is probable that all air obstructing water flow had been removed. This, in fact, may not be the only explanation for the levelling off of 'k' after 150 hours. A slow development of green colouration, noticeable through the transparent container, indicated gradual build up of algal growth in the pore system. This build up of algae may have led to blocking of certain pores, thus off-setting the effect of air removal from other pores. In attaining a constant flow rate, it is therefore possible that these two processes were eventually acting in equal and opposite directions. It is perhaps more reasonable to assume, however, that the constant 'k' value arose from the fact that both the algal build up and air dissolution processes had become static with time.

(b) Correlation of 'h_s' – 'H' with Time

It was considered desirable to plot total pressure loss in each tube against time, in preference to hydraulic head against time, as the former value resulted in a family of curves the differential values of which and order of magnitude, at any one time, were

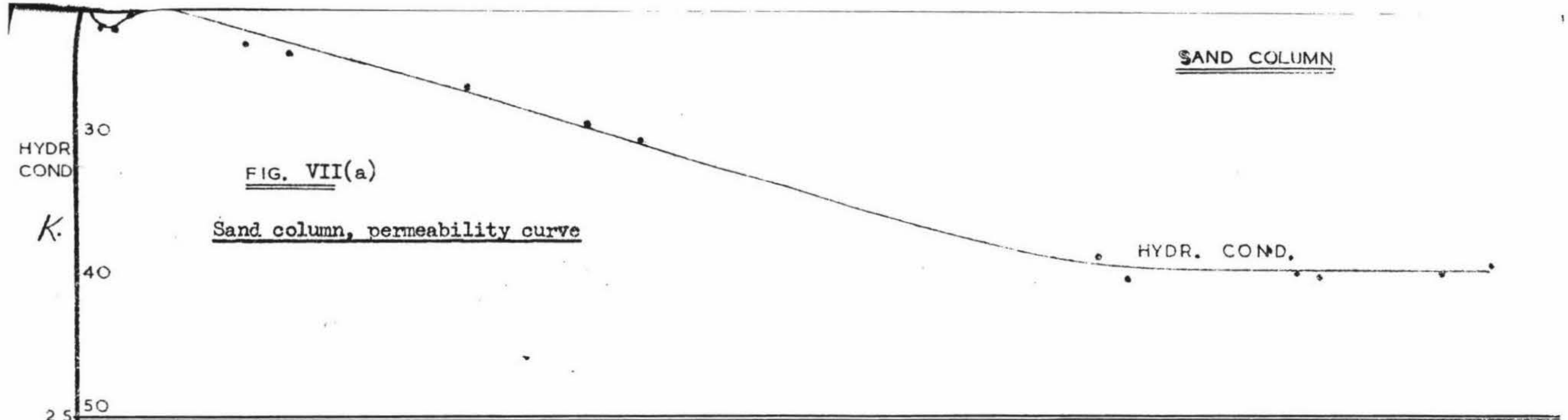


FIG. VII(a)

Sand column, permeability curve

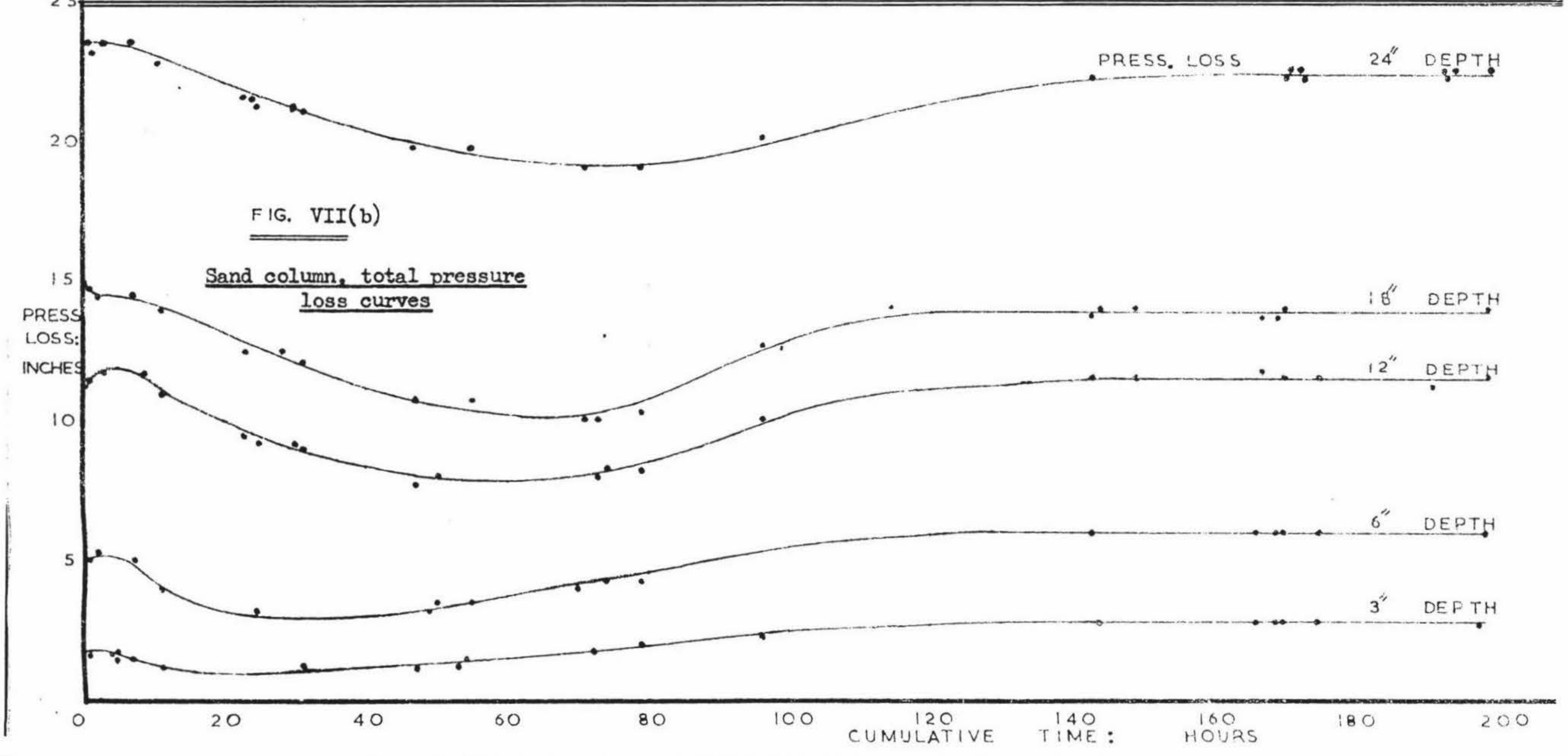


FIG. VII(b)

Sand column, total pressure loss curves

directly proportional to the relative impedances of the arbitrary profile layers bounded by the positions of the piezometer tubes. The family of curves of 'h_s' - 'H' as a function of time is given in Figure VII(b). Stable hydraulic pressures at each of the 3, 6, 12, 18 and 24 inch depths in the profile were attained after 130 - 140 hours. There appears to be no completely satisfactory explanation for the three stage pressure loss curves exhibited at each successive depth, especially when this family of curves is examined in conjunction with that of 'k' (Fig. VII(a)).

(c) Correlation of 'k' with 'h_s' - 'H'

The correlations of 'h_{s3}' - 'H_3', 'h_{s6}' - 'H_6', 'h_{s12}' - 'H_{12}', 'h_{s18}' - 'H_{18}' and 'h_{s24}' - 'H_{24}' with 'k' for the same time intervals is assessed by comparing the shapes of the family of pressure loss - time curves with that of 'k' as a function of time, all of which are included in Figure VII. There appears to have been little consistent correlation between 'k' and pressure loss at any point in the profile, until 150 hours elapsed, after which both sets of data remained at a constant level until the termination of the experiment. As would be expected, in the early stages of the experiment, the decrease in the loss of head during the period from 5 - 30 hours (at 3 and 6 inch depths) and the period from 5 - 65 hours (at 12, 18 and 24 inch depths), followed the trend of the increasing 'k' in the flow rate curve. However, the resumption of larger hydraulic pressure losses after these times appears to require a more complex explanation, especially when it was noted that 'k' continued to rise during the fall off of hydraulic pressures to their stable values indicated after 150 hours. No attempt will be made to suggest possible explanations of this situation, as insufficient applicable evidence is available from this particular experiment to substantiate any such hypotheses.

(d) Examination of Hydraulic Head Differentials throughout the Profile

Based on analogy with electromotive force principles and general physical and hydraulic analytical techniques, examination of hydraulic head distributions within the profile yielded data directly proportional to the relative impedance to water flow of the arbitrary profile layers examined. With the sand column tested, the 'h_s' - 'H' value at any selected point in the profile was governed by the total impedance of the porous material preceding it. Hence, the differential values of 'h_s' - 'H' (making allowance for the increase of 'h_s' with depth) at any two selected points in the profile, is a direct indication of the impedance to water flow of the layer between these two points.

The hydraulic gradient between any two adjacent points was calculated by dividing the difference between the 'h_s' - 'H' values for the points in question by the distance between them. Table V(a), abstracted from Appendix VI, lists the mean hydraulic gradients between all adjacent piezometer tubes, together with the respective standard errors of the means. The means were calculated from sets of ten readings for each tube. These readings were over a time range from 20 - 190 accumulated hours (inclusive), this being a period over which the pressure loss differentials were considered to have become reasonably constant (Fig. VII(b)). The standard statistical 't' test was applied to the data to establish significant differences between means at the 0.1% level of probability. Such a level of probability was considered satisfactory, as it ensured that only relatively outstanding differences between means would be found to be significantly different (d 0.001 = 3.92). Such a requirement is reasonable when it is realized that all readings of 'h_s' - 'H' values in the piezometer tubes were taken to within the nearest $\frac{1}{4}$ inch. Consequently the 1% and 5% levels of probability would have introduced a false accuracy into the analysis of the data.

Depth boundaries of layers	0" - 3"	3" - 6"	6" - 12"	12" - 18"	18" - 24"	24" - 30"
Mean hydr. gradient	0.74	0.93	0.86	0.42	1.39	1.49
S.E. of Mean	±0.075	±0.059	±0.011	±0.019	±0.035	±0.069

TABLE V(a)

Mean hydraulic gradients of the arbitrary layers of the sand column (normal flow direction)

Where non-significant differences between gradient means were apparent, the means of the layers concerned were re-grouped under an overall mean, and it is this value that determined the value of relative impedance assigned to the overall layer. Taking the greatest overall mean gradient (i.e. the averages of the means between 18 and 24 inches, and 24 and 30 inches) as an arbitrary unity value, relative impedance values were computed for all layers (Table V(b)). It must be noted that, because of the widely differing experimental conditions and techniques, no attempt will be made to compare the values of relative impedances derived from the sand column with those derived from soil cores. Indeed, the arbitrary unity values in both cases are not identical, so that no comparison is possible.

Depth boundaries of layers	0" - 3"	3" - 6"	6" - 12"	12" - 18"	18" - 24"	24" - 30"
Relative impedances (R.I.)	0.58	0.58	0.58	0.29	1.00	1.00

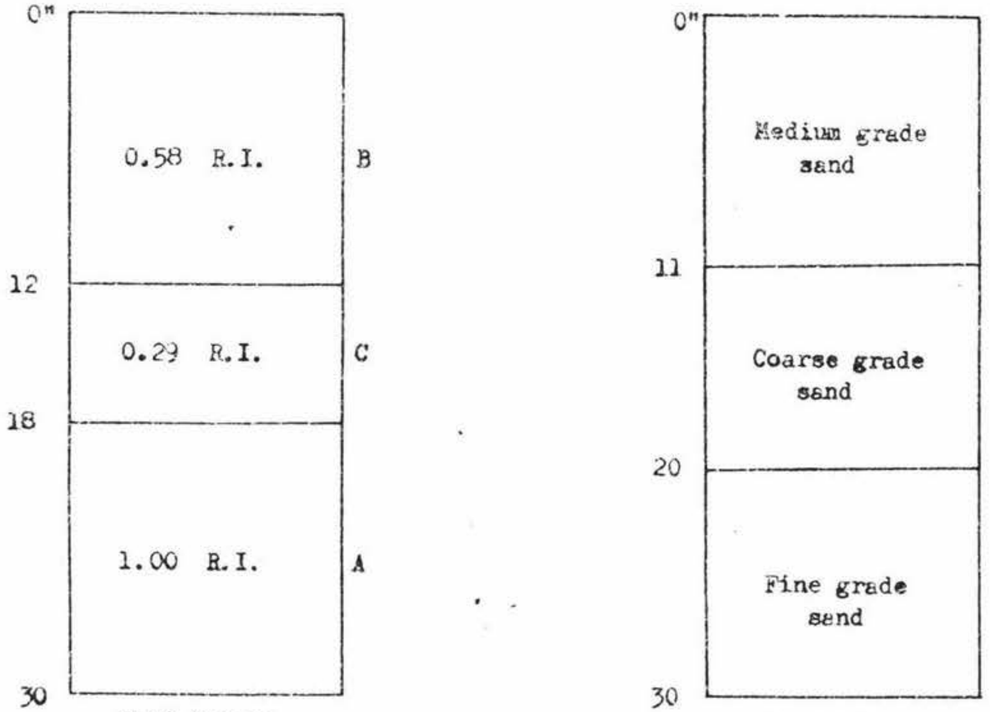
TABLE V(b)

Relative Impedances of the arbitrary layers of the sand column

(normal flow direction)

Figure VIII(a) is a diagrammatic representation of the sand profile compiled from analyses of the experimental data, while Figure VIII(b) represents the sand profile as it actually was. It will be noted that in the theoretical profile, the lettering 'A', 'B' and 'C' is also assigned to the layers. This is to provide a quick reference to the layers in the order of their decreasing impedance.

It can be seen from Figure VIII that the similarity between the theoretical and actual profiles is quite distinct. However, it was felt that the provision of tubes at 3 inch intervals throughout the profile would have increased the accuracy of allocation of the horizon boundaries. Consequently, all subsequent experiments performed with soil cores utilized six or eight tubes at 3 inch (and occasionally 6 inch) intervals.



Sand Column
(theoretical profile)

(a)

Sand Column
(actual profile)

(b)

FIGURE VIII

IV HYDRAULIC TESTS ON "UNDISTURBED" SOIL CORES FROM THE ONGLEY PARK PROFILE

Specifications of the experimental conditions for the testing of a battery of six cores were as listed below:-

Core identifications	:	G_2, H_2, I_2, J_2, K_2 and L_2 (all cores were from the same soil type, and taken from within a 10 sq.yd. area).
Dimensions of cores	:	29 inches long, with an infiltrating surface area of approximately 6 sq. inches.
Permeating liquid	:	Tap water.
Liquid supply	:	Overflow reservoir.
Flow direction	:	Normal.
Static surface head	:	9.5 inches of water for cores G_2, H_2 and I_2 9.25 inches of water for cores J_2, K_2 and L_2 .
Hydraulic head at core effluents	:	1.75 inches of water for all cores.
Overall hydraulic gradients	:	0.27 for cores G_2, H_2 and I_2 0.26 for cores J_2, K_2 and L_2.
Control of soil organisms	:	Continual U.V. light treatment of the vegetative surfaces of all cores.
Temperature	:	Controlled air temperature at $68 \pm 2^{\circ}F$.
Approximate soil moisture contents at initiation of the experiment	:	Slightly less than field capacity.
Nomenclature	:	The static head at a point in the profile is designated by 'h_s' followed by a subscript number indicating depth in inches. The hydraulic head at a point in the profile is designated by 'H' followed by a subscript number indicating depth in inches.

The cause of the fall of static surface head from 9.5 inches to 9.25 inches for the three cores furthermost from the supply reservoir (J_2, K_2 and L_2), was jointly attributed to a frictional loss in the common supply line, and the influence of "draw-off" from the common supply line of the preceding three cores (G_2, H_2 and I_2). In fact, there was a gradual fall of head, along the supply line, of 0.25 inches over the range of the six cores, but as all measurements of 'H' in the piezometer tubes were made to the nearest $\frac{1}{4}$ inch, there was little benefit in recording a decline in static surface head until a distance from the reservoir was reached where the decline approached the nearest $\frac{1}{4}$ inch.

(a) Correlation of 'k' with Time

Results from core J_2, which was tested along with G_2, H_2, I_2, K_2 and L_2 in an identical manner, have been excluded from this consideration. Hydraulic conductivity values for this core remained at levels far less than the average of the cores. While this, in itself, was not sufficient reason to condemn a core from a soil of known low intrinsic permeability, the apparent cause of the low flow rate was due to an abnormally high surface impedance. The result of such a high surface impedance was that the overall hydraulic gradient throughout the remaining length of the core was reduced to a value approximating 0.07. With such a low gradient, only extremely large variations in internal impedance would be detected. It is possible that the high surface impedance was a direct result of inadvertently sampling from an area of ground previously compacted by a tractor or implement wheel - perhaps those of the sampling tractor.

Hydraulic conductivity, 'k' , was computed directly in the Darcy equation

$$v = ki$$

(where 'v' is the flow rate in inches per hour, and 'i' is the hydraulic gradient). The flow rate, in inches per hour, was calculated from mls. per hour utilizing the expression

$$\text{ins./hr.} \doteqdot \frac{\text{mls./hr.}}{100}$$

It was felt that this approximation was justified because of the physical limitations of accurately determining the infiltrating surface area of the core.

In Figures IX(a), X(a), XI(a), XII(a) and XIII(a), hydraulic conductivity, 'k' , as a function of time, is shown for each of the cores G_2, H_2, I_2, K_2 and L_2 respectively for a total duration of $188\frac{1}{4}$ hours. For convenience of comparison of 'k' values with the

(cont. pg. 113)

Core G_2

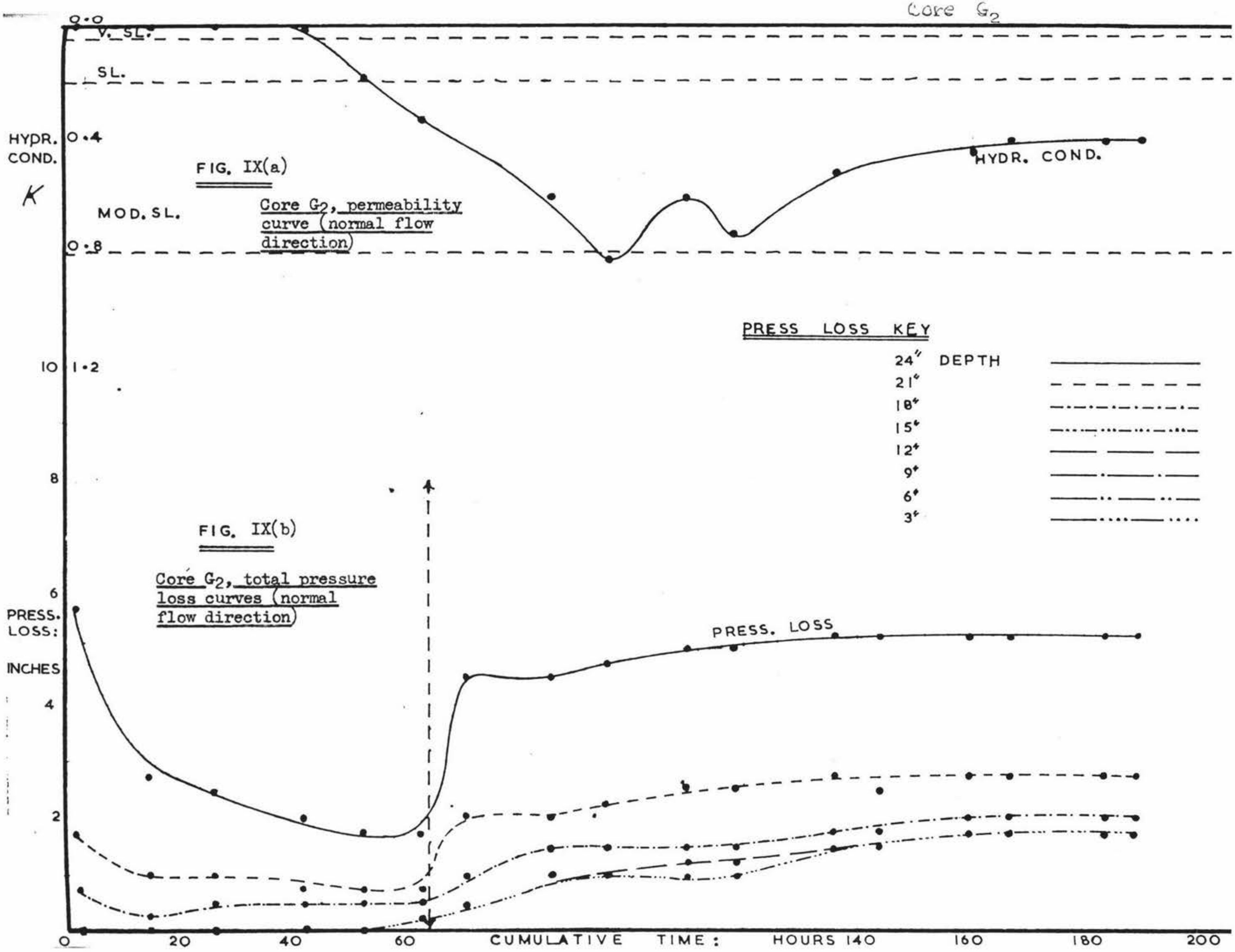


FIG. IX(a)

Core G_2, permeability curve (normal flow direction)

FIG. IX(b)

Core G_2, total pressure loss curves (normal flow direction)

Core H_2

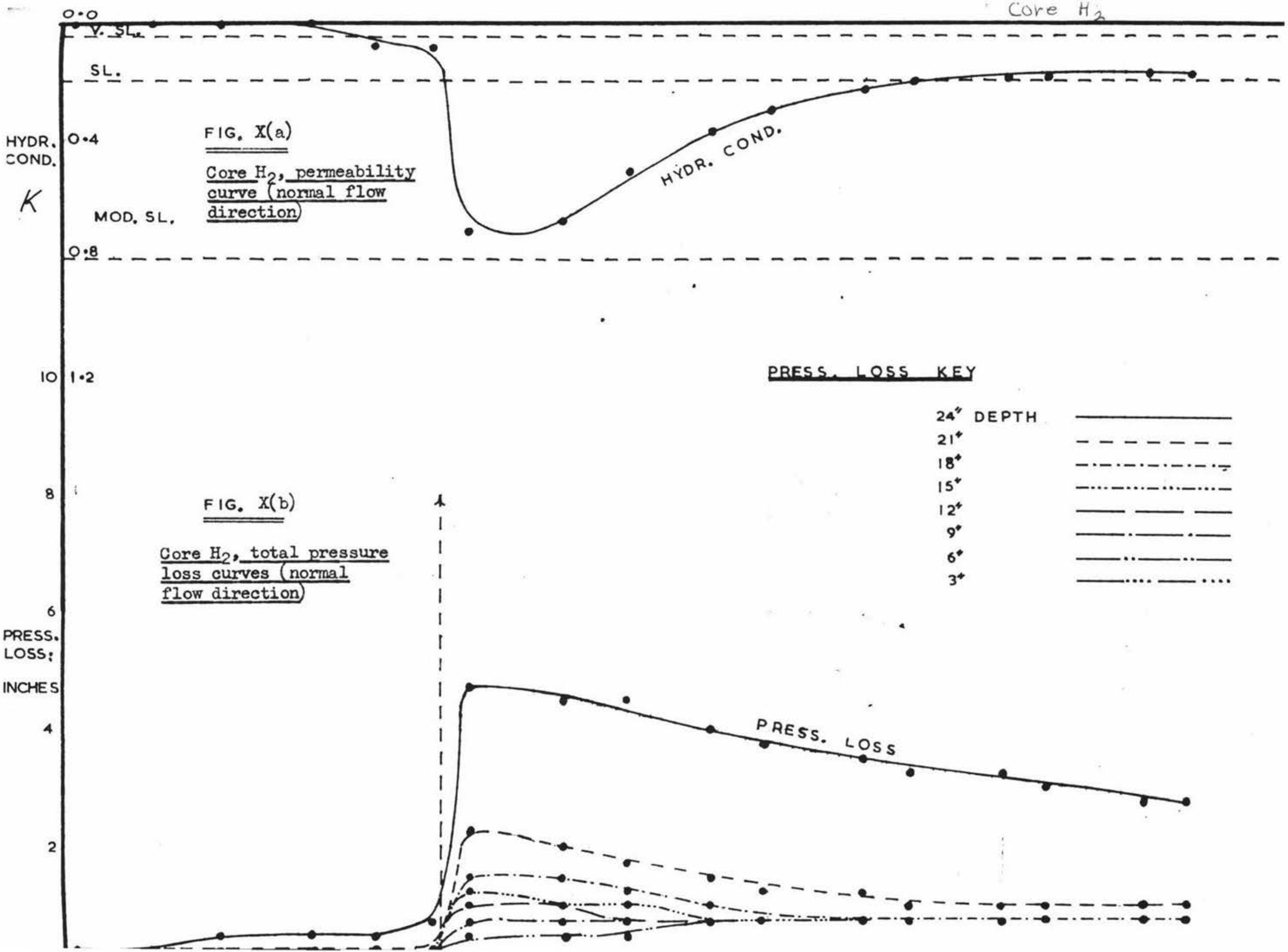


FIG. X(a)

Core H_2, permeability curve (normal flow direction)

FIG. X(b)

Core H_2, total pressure loss curves (normal flow direction)

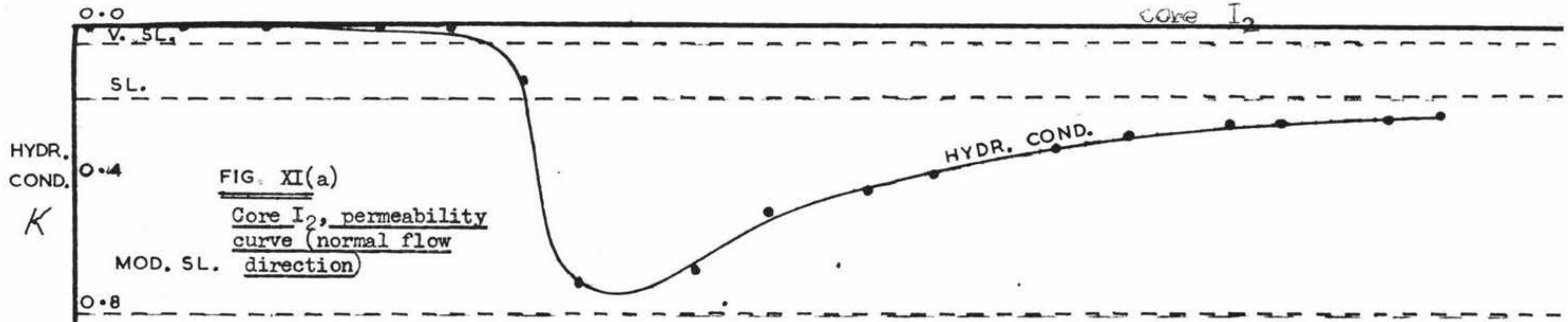


FIG. XI(a)

Core I_2, permeability curve (normal flow direction)

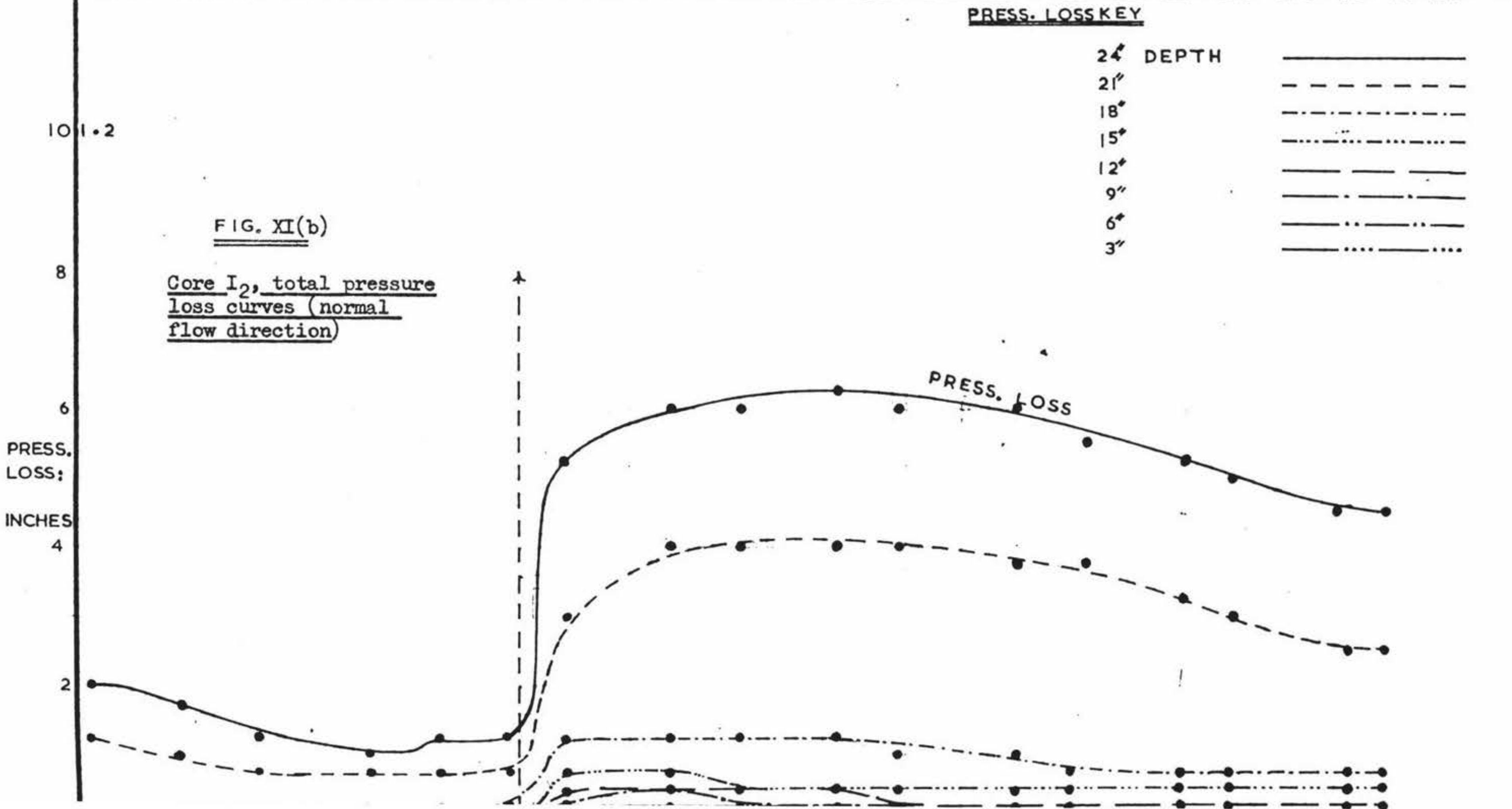


FIG. XI(b)

Core I_2, total pressure loss curves (normal flow direction)

Core K₂

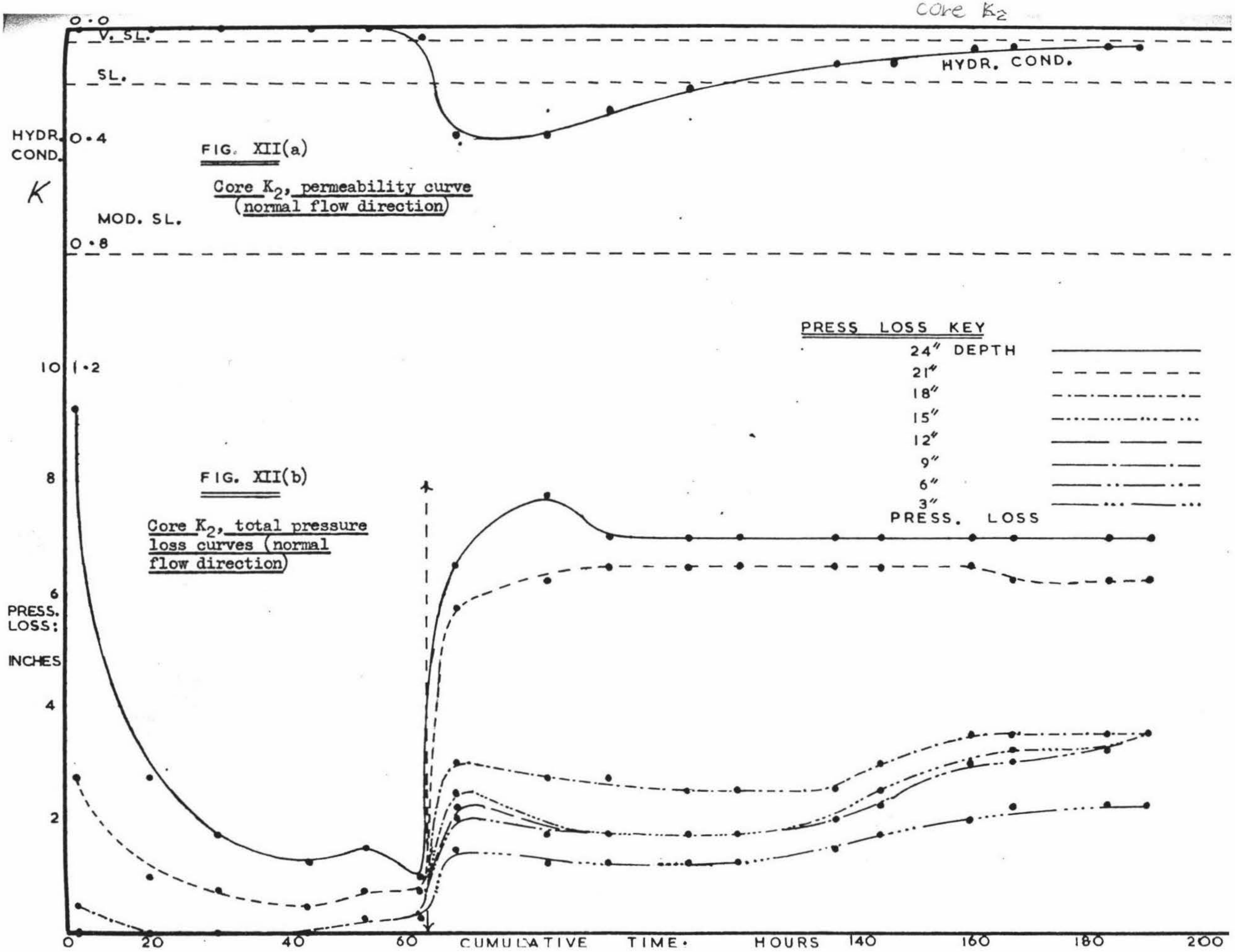


FIG. XII(a)

Core K_2, permeability curve (normal flow direction)

FIG. XII(b)

Core K_2, total pressure loss curves (normal flow direction) core L_2

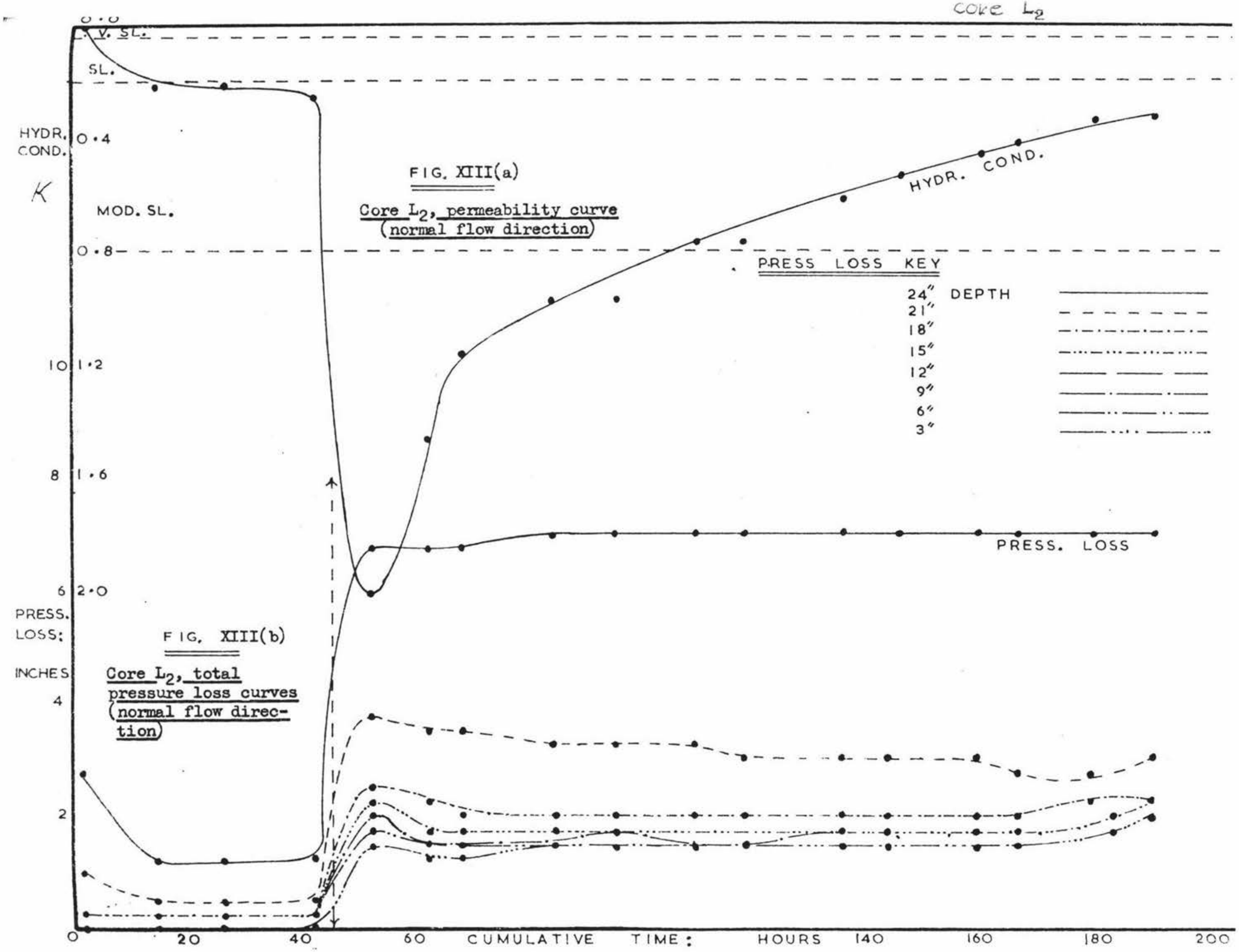


FIG. XIII(a)

Core L_2, permeability curve (normal flow direction)

FIG. XIII(b)

Core L_2, total pressure loss curves (normal flow direction) respective families of total pressure loss curves in Figures IX(b), X(b), XI(b), XII(b) and XIII(b), it will be noted that the ordinates in Figures IX(a), X(a), XI(a), XII(a) and XIII(a) are labelled with numerical values increasing down the page. It was considered desirable to adopt this graphical procedure in preference to plotting the reciprocal of 'k' against time, as '$\frac{1}{k}$' is not a unit of universal recognition. As with the sand column graphs, reversing the direction of the hydraulic conductivity ordinate allowed the universally acceptable 'k' to be plotted against cumulative time, and have the same abscissa values as the family of total pressure loss curves.

The broken horizontal lines, parallel with the abscissae and intersecting the ordinates at 'k' = 0.05, 0.2, and 0.8 respectively, represent the boundaries of the three lowest of O'Neal's (1952) permeability categories, viz. extremely slow (less than 0.05 inches per hour), slow (0.05 - 0.2 inches per hour), and moderately slow (0.2 - 0.8 inches per hour).

No attempt was made in this experiment to reproduce the generalized curve of Allison (1947). Previous experimental results (now unfortunately unavailable) demonstrated the three phase flow rate - time relationship quite clearly, and it was considered unnecessary to duplicate these curves.

Distinct odours, noticeable on the termination of previous experiments, indicated anaerobic microbiological activity in at least the surfaces of the cores. Because of this, and supported by the findings of Allison (loc.cit.) and McCalla (1950), it was considered that the total duration of an experiment, with cores under prolonged "saturation", should be minimized to avoid undue blocking of the pores with microbial products and residues. Hence, after 42.25 accumulated hours (for core L_2) and after 63.00 hours (for cores G_2, H_2, I_2 and K_2) a vacuum was applied to the effluents of the cores. The time (in cumulative hours) at which this occurred is shown as a broken line, double headed arrow, parallel to the ordinates in Figures IX(a), X(a), XI(a), XII(a) and XIII(a). This vacuum was in the order of 5 - 6 inches of mercury and was maintained for a short time only in order to avoid the possible formation of scoured channels within the cores. The result of this vacuum application was to accelerate the removal of the air that had become trapped in the cores. It is considered that, in fact, this technique hastened the completion of phase 2 of Allison's (1947) curve, the shape of which has been generally accepted as being dominantly attributable to gradual dissolution and removal of air from the porous system. It is seen from the experimental curves that the hydraulic conductivity of all cores decreased gradually from the peak (which immediately followed the vacuum application) to approach stable levels within the slow or moderately slow permeability ranges. The shapes of the permeability curves, after the peaks, are very similar to that given by

Allison (loc. cit.) for phase 3 of his generalised curve. There appears to be no reason to doubt that the cause of this decline was predominantly a microbial build-up in the cores. On the contrary, there was the evidence of a distinctive odour (though perhaps somewhat subjective) to support suggestions that the decline was, at least in part, due to an increase in microbial population. Another suggested process which may have jointly contributed to the decline, was the overall dispersion of soil colloidal material within the profile. This latter suggestion is put forward with reservations, however, as precise chemical analysis of the permeating water was not performed, and little was known of its composition or 'pH' fluctuations.

(b) Correlation of 'h_{s0}' - 'H' with Time

It was considered desirable to plot total pressure loss values against time in preference to hydraulic head against time, as the former values resulted in a family of curves, the differential values of which were directly proportional to the relative impedances of the arbitrary experimental layers. It will be noted that, where any two piezometer tubes on one core recorded identical 'h_{s0}' - 'H' values for any length of time, only the curve for the tube at the greatest depth is represented on the graph for that period of time.

Figures IX(b), X(b), XI(b), XII(b) and XIII(b) represent the families of curves of 'h_{s0}' - 'H' as a function of time for cores G_2, H_2, I_2, K_2 and L_2 respectively. With the initial extremely slow movement of water through the cores (up to the time at which a vacuum was applied to the core effluents), the piezometer tubes all tended to indicate the static head of 9.5 or 9.25 inches of water applied to the soil surfaces. However, with the induced acceleration of flow, the effect on the pressure loss readings was immediate, and from that time until the termination of the experiment, the height of water in any one tube at any one time could safely be assumed to indicate the hydraulic head, 'H' , at that depth in the profile.

As can be seen from a study of the respective curves over the time interval from 86.75 - 188.25 cumulative hours, the variation with time of an individual piezometer tube was not always consistent with that of the other tubes along the profile in any one core. There are several possible explanations of this:-

(i) There may have been a time lag between the effects of some factors influencing pressure distribution down through the profile.

(ii) Microbiological activity, leading to pressure variations, may have been more concentrated in one area of the core than in another.

(iii) If a particular piezometer tube were partially blocked at its intake, an overall pressure drop, concerning say four tubes, may have taken longer to be registered in this one particular tube than in any of the others.

(iv) The migration of soil macroorganisms (such as earthworms) may have had a localised effect in freeing, blocking or the production of channels which were capable of conductance at very little pressure loss.

(v) The influence of accumulated air bubbles at the base of individual piezometer tubes.

(vi) There may have been more pronounced effects of colloidal dispersion in horizons of greater clay content than in those of lower clay percentage.

Whatever the causes of variability, the individual tubes in most cores (with the exception of H_2 and I_2, Figs. X(b) and XI(b)) appeared to have settled down to reasonably steady, or at least parallel, total pressure loss curves after about 90 hours. The processes leading to the attainment of relatively stable pressure loss readings with time, would be expected to be closely related to those processes normally attributed to the causes of the levelling off of hydraulic conductivity with time. It has been the author's experience, however, that this was not necessarily true with the cores tested.

An interesting phenomenon occurred between 110.5 hours and 118.0 hours in core G_2, Figure IX(b). During this time, the tube at 15 inches depth registered a smaller pressure drop than its counterpart at 12 inches depth. Had this been a prolonged difference throughout the duration of the experiment (as was the case in a previous core), a possible explanation would have been that the tube at 15 inches, by chance, had been placed at or near the opening of a worm channel which may have bypassed the tube at 12 inches. However, the temporary nature of the phenomenon suggests the possibilities of an accumulated air bubble in the base of the 15 inch tube, a time lag of reaction in the 15 inch tube due to partial blocking of its inlet, or the temporary unblocking of a worm channel situated as described above. The latter possible cause could have been initiated by the migration of an earthworm.

(c) Correlation of 'h_{s0}' - 'H' with 'k'

By comparison of the curves in Figures IX(a), X(a), XI(a), XII(a) and XIII(a) with the respective families of curves in Figures IX(b), X(b), XI(b), XII(b) and XIII(b), assessment of the correlation between the two general shapes of the curves for any one core can be made.

Contrary to expectations, it is seen with all cores (except possibly G_2 and K_2, Figs. IX and XII) that as the flow rate decreased, the registered total loss of head in most piezometer tubes also decreased, or at best remained constant (i.e. 'H' tended to increase with decreasing 'k'). This relationship appears to have no simple satisfactory explanation. One would expect that if a flow rate decrease was the result of a decrease in the total number of conducting pores in the system (Allison 1947, McCalla 1950), then such blocking of pores would have tended to increase the impedance of at least a portion of the profile. With an increased impedance in a particular profile portion, pressure loss increases would have also been registered in all the piezometer tubes on the "low pressure" side of the layer that included this portion of the core. That this, in fact, did not occur (and in some cases the opposite occurred) during the time the experiment was in process, can only be explained by suggesting that several complementary and contrary phenomena were responsible. Any suggested identification of these phenomena, in view of the lack of applicable evidence available from these experiments to support them, would be subjective in extreme and would be of questionable validity. Nevertheless, over most of the time range of the experiment, despite the sometimes unexplainable time trends, notable differences in hydraulic gradients throughout each core were consistently recorded. The unmistakeable trend of these differentials in five of the six cores tested, justified closer examination of the data in order to obtain some appreciation of the relative impedance to water flow of the horizons making up the profile.

(d) Examination of 'h_s' - 'H' Distribution within the Profile as a Basis for the Allocation of Relative Impedance Values to the Arbitrary 3 and 5 inch Layers

The hydraulic gradient that existed between any two piezometer tubes, reflected directly the frictional resistance to water flow of the 3 inch layer bounded on either side by the position of the tubes. Similarly, the hydraulic gradient that existed between the infiltrating surface or effluent ejection tube and its nearest piezometer tube, reflected directly the frictional resistance to water flow of the 3 inch or 5 inch layer between these respective points. By examining each tube in turn, hydraulic gradients were calculated as follows:-

Suppose, as in core K_2 (Fig. XII(b)), at 166.25 accumulated hours, the tube at 3 inches depth indicates a total pressure drop of 2.25 inches (i.e. 'h_{s0}' - 'H_3' = 2.25 inches), then the hydraulic gradient between these two points is given by $\frac{2.25}{3.00}$. However, the total pressure loss indicated at 6 inches depth ('h_{s0}' - 'H_6') was in this case 3.00 inches (i.e. 'h_{s3}' - 'H_6' = 0.5 inches). The hydraulic gradient between

3 and 6 inches depth is then $\frac{0.50}{3.00}$. In other words, the static head, 'h_s', on the "high pressure" side of any 3 inch layer is indicated by the hydraulic head, 'H', of the "low pressure" side of the preceding 3 inch layer.

Below, in Tables VI(a), VII(a), VIII(a), IX(a) and X(a), are listed the mean hydraulic gradients computed from sets of data for each piezometer tube of each core. The sets of data represent values taken at 10 time intervals between 86.75 accumulated hours and 188.25 hours (inclusive). The statistical computed standard errors of the means are also indicated. The arbitrary choice of the 10 time intervals listed (Appendices VIII, IX, X, XI and XII) was governed by the shape of the total pressure loss - cumulative time curves (Figs. IX(b), X(b), XI(b), XII(b) and XIII(b)), and represent values taken where it was considered that the initial influence of the vacuum application to the core effluents had been largely dissipated.

In order to statistically examine the significant differences between the gradient means within a core, it was necessary to partially disregard the lack of complete overall consistency between individual piezometer tubes (as discussed in subsection (b) above). This apparent inconsistency was only partially disregarded, because computation itself, of the standard error of the means, took into account the variations of any one tube about the mean of the ten readings considered. Comparisons were made between the means of the gradients for each of the eight tubes in each core. Adopting the standard 't' test, significant and non-significant differences between any two (not necessarily adjacent) gradients across the arbitrary layers in the profile, were ascertained at the 0.1% level of probability. The difference for significance between any two gradients in any core was 3.92.

As with the sand column experiment, the 0.1% level of probability was selected as being suitable because with the 1% and 5% levels, a large number of significantly different layers (up to 8 in one 29 inch core) were identified. It is unreasonable, and suggests false accuracy to separate so many layers (many of which differed by only small amounts) when all recordings of 'h_{s0}' - 'H' in the piezometer tubes were to the nearest $\frac{1}{4}$ inch. By adopting a statistical analysis at the 0.1% level of probability, the theoretical profiles compounded usually became divided into 3, 4 and 5 different horizons, and thereby indicated as significant, only relatively large differences between layers, and grouped as hydraulically homogeneous, layers with only small mean hydraulic gradient differences.

Tables VI(b), VII(b), VIII(b), IX(b) and X(b) list values of relative impedance.

(cont. pg. 121)

Depth boundaries of layers	0"-3"	3"-6"	6"-9"	9"-12"	12"-15"	15"-18"	18"-21"	21"-24"	24"-29"
Mean hydr. gradient	0.48	0.00	0.00	0.00	0.00	0.10	0.27	0.84	0.54
S.E. of mean	±0.036	±0.000	±0.000	±0.000	±0.000	±0.012	±0.016	±0.009	±0.017

TABLE VI(a)

Mean hydraulic gradients of the arbitrary layers of core G_2
(normal flow direction)

Depth boundaries of layers	0"-3"	3"-6"	6"-9"	9"-12"	12"-15"	15"-18"	18"-21"	21"-24"	24"-29"
Mean hydr. gradient	0.23	0.017	0.00	0.0083	0.0083	0.034	0.13	0.75	0.85
S.E. of mean	±0.011	±0.011	±0.000	±0.026	±0.026	±0.019	±0.012	±0.035	±0.041

TABLE VII(a)

Mean hydraulic gradients of the arbitrary layers of core H_2
(normal flow direction)

Depth boundaries of layers	0"-3"	3"-6"	6"-9"	9"-12"	12"-15"	15"-18"	18"-21"	21"-24"	24"-29"
Mean hydr. gradient	0.083	0.00	0.0083	0.017	0.066	0.14	0.84	0.68	0.45
S.E. of mean	±0.000	±0.000	±0.026	±0.011	±0.011	±0.022	±0.049	±0.015	±0.045

TABLE VIII(a)

Mean hydraulic gradients of the arbitrary layers of core I_2
(normal flow direction)

Depth boundaries of layers	0"-3"	3"-6"	6"-9"	9"-12"	12"-15"	15"-18"	18"-21"	21"-24"	24"-29"
Mean hydr. gradient	0.57	0.24	0.00	0.017	0.19	0.00	1.13	0.23	0.78
S.E. of mean	±0.047	±0.029	±0.000	±0.011	±0.030	±0.000	±0.061	±0.033	±0.025

TABLE IX(a)

Mean hydraulic gradients of the arbitrary layers of core K_2
(normal flow direction)

Depth boundaries of layers	0"-3"	3"-6"	6"-9"	9"-12"	12"-15"	15"-18"	18"-21"	21"-24"	24"-29"
Mean hydr. gradient	0.53	0.050	0.0083	0.033	0.00	0.075	0.32	1.32	0.75
S.E. of mean	± 0.018	±0.014	±0.026	±0.014	±0.000	±0.0083	±0.030	±0.012	±0.000

TABLE X(a)

Mean hydraulic gradients of the arbitrary layers of core L_2
(normal flow direction)

These values were computed from the mean gradients, taking the highest value for the five cores (viz. 1.32, being the gradient between 21inches and 24 inches depth in core L_2) as an arbitrary unity value. The values, being relative, have no units, and individual values for each layer are given. Where any number of layers in any one core were found to have mean gradients not significantly different, the relative impedance was computed from an overall mean value of the means of these particular layers.

In Figure XIV, each horizon of each core was assigned a relative impedance value, and the depth boundaries of the horizons are indicated. Consequently, convenient recognition of that horizon (or those horizons) which exhibited the least permeability, is possible. It must be noted that the allocation of relative impedance values to all horizons in all cores with a common unity value, does not indicate the intention of the author to make critical quantative comparisons between cores. Such comparisons would be largely invalid due to the small number of replications possible. Had data from previous trials (utilizing a further twentyfour cores) been still available, such comparisons may have been valid.

In the diagrammatic representations of the theoretical profiles, given below, relative impedance values are shown, but in the examination of individual cores the lettering 'A', 'B', 'C' etc. allows rapid identification of layers in order of increasing permeability. The layer of least permeability is represented by 'A', the next by 'B', and so on.

It is considered that the arbitrary division of the profiles into 3 inch and 5 inch layers for experimental purposes, was justified in that analysis of the layers, enabled the majority of horizon boundaries to be pinpointed to within $1\frac{1}{2}$ inches. This, of course, required the establishment of an horizon with a maximum possible error of 3 inches in its total thickness, which is considered to be sufficiently accurate, especially when dealing with soils where horizon boundaries tended to be merging.

Depth boundaries of layers	0"-3"	3"-6"	6"-9"	9"-12"	12"-15"	15"-18"	18"-21"	21"-24"	24"-29"
Relative impedances (R.I.)	0.39	0.00	0.00	0.00	0.00	0.076	0.20	0.64	0.39

TABLE VI(b)

Relative impedances of the arbitrary layers of core G_2
(normal flow direction)

Depth boundaries of layers	0"-3"	3"-6"	6"-9"	9"-12"	12"-15"	15"-18"	18"-21"	21"-24"	24"-29"
Relative impedances (R.I.)	0.17	0.015	0.015	0.015	0.015	0.015	0.098	0.61	0.61

TABLE VII(b)

Relative impedances of the arbitrary layers of core H_2
(normal flow direction)

Depth boundaries of layers	0"-3"	3"-6"	6"-9"	9"-12"	12"-15"	15"-18"	18"-21"	21"-24"	24"-29"
Relative impedances (R.I.)	0.039	0.039	0.039	0.039	0.039	0.039	0.64	0.52	0.34

Note: Layers 0"-3", 3"-6", 6"-9", 9"-12", 12"-15" and 15"-18" have all been grouped together with a common gradient of 0.039. Although inter-comparisons of the six layers were not all necessarily non-significant, it was considered that the distribution of the range of non-significant differences justified the treatment of all the layers as one homogeneous horizon.

TABLE VIII(b)

Relative impedances of the arbitrary layers of core I_2
(normal flow direction)

Depth boundaries of layers	0"-3"	3"-6"	6"-9"	9"-12"	12"-15"	15"-18"	18"-21"	21"-24"	24"-29"
Relative impedances (R.I.)	0.43	0.16	0.006	0.006	0.16	0.006	0.86	0.16	0.59

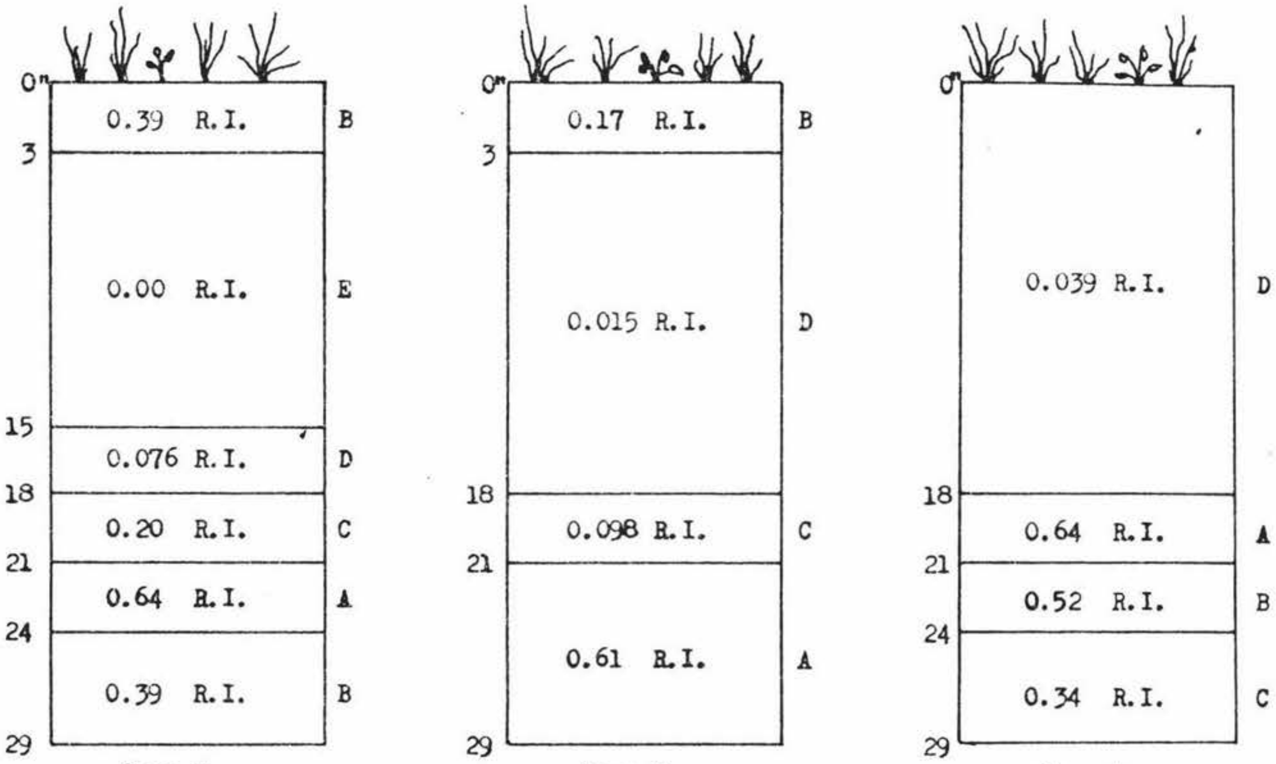
TABLE IX(b)

Relative impedances of the arbitrary layers of core K_2
(normal flow direction)

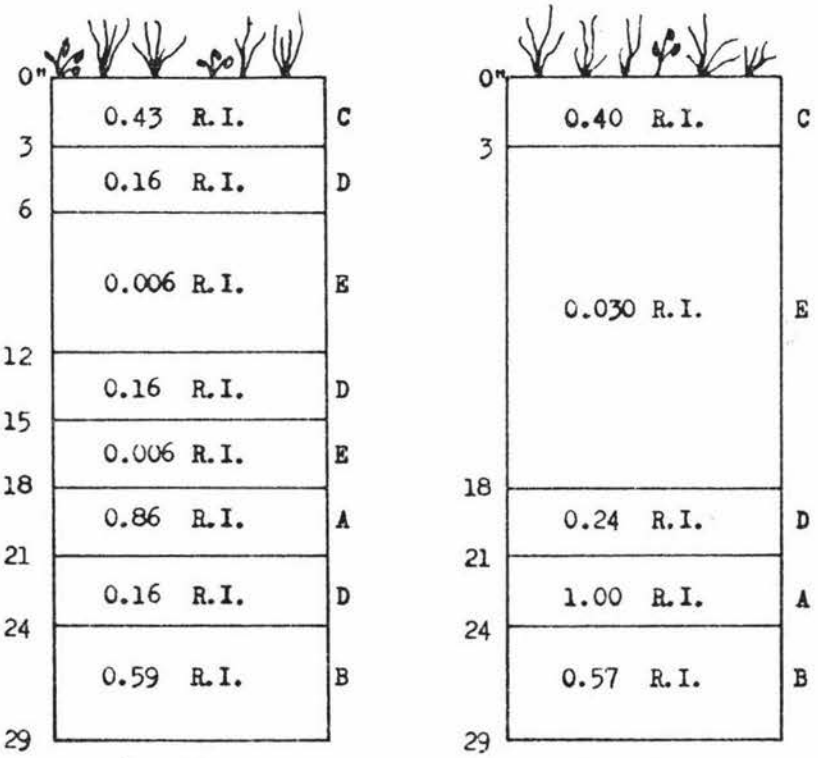
Depth boundaries of layers	0"-3"	3"-6"	6"-9"	9"-12"	12"-15"	15"-18"	18"-21"	21"-24"	24"-29"
Relative impedances (R.I.)	0.40	0.030	0.030	0.030	0.030	0.030	0.24	1.00	0.57

TABLE X(b)

Relative impedances of the arbitrary layers of core L_2
(normal flow direction)



Core G_2 Core H_2 Core I_2



Core K_2 Core L_2

FIG. XIV

The theoretical profiles of cores G_2, H_2, I_2, K_2 and L_2 (normal flow direction)

V HYDRAULIC TESTS ON "UNDISTURBED" SOIL CORES FROM THE ONGLEY PARK PROFILE, WITH THE FLOW DIRECTION REVERSED

Specifications of the experimental conditions for the testing of a battery of six cores were as listed below:-

Core identifications	G_2, H_2, I_2, J_2, K_2 and L_2 (all cores were from the same soil type, and taken from within a 10 sq. yd. area).
Dimensions of cores	29 inches long, with an infiltrating surface area of approximately 6 sq. inches.
Permeating liquid	Tap water.
Liquid supply	Overflow reservoir.
Flow direction	Reversed.
Static surface head	9.5 inches of water for cores G_2, H_2 and I_2 9.25 inches of water for cores J_2, K_2 and L_2 .
Hydraulic head at core effluents	1.75 inches of water for all cores.
Overall hydraulic gradients	0.27 for cores G_2, H_2 and I_2 0.26 for cores J_2, K_2 and L_2 .
Control of soil organisms	No U.V. light treatment, as earthworms were unlikely to emerge from the infiltrating surface.
Temperature	Controlled air temperature at 68 ± 2°F .
Approximate soil moisture contents at initiation of the experiment	"Saturation".
Nomenclature	The static head at a point in the profile is designated by 'h_s' followed by a subscript number indicating the distance from the vegetative surface, in inches. The hydraulic head at a point in the profile is designated by 'H' followed by a subscript number indicating the distance from the vegetative surface, in inches.

The testing of cores G_2, H_2, I_2, J_2, K_2 and L_2 with the flow direction reversed was undertaken by simply reversing the cores in their mountings on the swivel table, so that the surfaces presented to the infiltrating water were, in fact, at points 29 inches from the vegetative surfaces of the normal profiles. The vegetative surfaces then represented the effluent ends of the cores. For convenience of comparison of results obtained in this manner with results previously obtained from the same cores, with the flow in a normal direction, the identification of individual piezometer tubes will remain as they were in subsection IV above. To avoid confusion, however, a tube located at a depth of say 12 inches below the vegetative surface in the normal profile will be referred to as being the 12 inch "depth" tube when dealing with the core mounted and tested in the reverse position. The inverted commas accompanying the word depth serve only to remind the reader that the identification of that point in inches depth, still has its datum at the vegetative surface. Thus, the nearest tubes to the infiltrating surfaces in all cores (when in the reverse position) will be at 24 inches "depth".

Apart from the clarification of nomenclature, all pertinent comments on the drop of the static surface head with distance from the reservoir, the calculation of 'k', the reasons underlying the graphical procedure of reversing the direction of the 'k' ordinates, the reasons underlying the plotting of total pressure losses against time, and the identification of the broken horizontal lines depicting permeability classes have all been dealt with in subsection IV and need no expansion in connection with the reversed flow direction experiments.

(a) Correlation of 'k' with Time

Results from the core J_2 were discarded for the same reasons as outlined in subsection IV(a) previously.

Results from cores K_2 and L_2 were also excluded from this consideration as both showed a marked increase in hydraulic conductivity over the values previously obtained with a normal flow direction. In addition, the increased 'k' values took place quite suddenly in both cases, and although they were showing signs of decreasing at the termination of the experiment, the 'k' values at no stage fell below the moderately rapid or rapid permeability classes. The increase in flow rate from core L_2 was almost undoubtedly attributable to the formation of scoured channels as a result of application of a vacuum to the core effluent for a short time. Although all cores were disconnected, reversed in their mountings, recharged, and reconnected, in the shortest possible time, some drainage of the profiles occurred and it was found necessary to re-apply the vacuum to the effluents of cores G_2, J_2 and L_2 to eliminate the small quantity of entrapped air in the cores (probably entering through the piezometer tubes). This entrapped air was delaying the time taken for these cores to reach equilibrium with the static surface head again. The time at which the vacuum was applied to core G_2 is shown as a broken line, double headed arrow parallel to the ordinates in Figure XV. In the case of core L_2, it appears that the vacuum application was detrimental. The increase in flow rate from core K_2 may have been due to a number of factors, not the least of which is the possible activity of earthworms producing new channels in the soil matrix. In Figures XV(a), XVI(a) and XVII(a), hydraulic conductivity as a function of time is shown for cores G_2, H_2 and I_2 respectively, for a total duration of $191\frac{1}{2}$ hours. It is noteworthy that for the majority of the duration of this experiment, the 'k' values of each of the cores remained within the same permeability classes as they had finished in in the previous experiment (Figs. IX(a), X(a) and XI(a)).

As was to be expected, after the initial increase following the changeover, flow rates remained at a constant level except that with core I_2 there was a slight continual increase in flow rate up to about 130 hours, after which it levelled off. Nevertheless, this increase at no stage resulted in the permeability of core I_2 shifting to a higher class after 30 hours. It would appear, then, that the curves shown in Figures XV(a), XVI(a) and XVII(a) (like their counterparts recorded previously with normal flow direction) represent the very latter stages of phase 3 of Allison's (1947) generalized permeability curve.

(b) Correlation of 'h_{s0}' - 'H' with Time

Again, as was to be expected, following almost immediately after $188\frac{1}{4}$ hours of prolonged normal flow, the 'h_{s0}' - 'H' values recorded from cores G_2, H_2 and I_2 with reversed flow, took a comparatively short time to settle down and thereafter their values remained reasonably steady, or parallel, until the termination of the experiment. The families of curves, representing the total pressure losses at successive "depths" for each of the cores, are shown in Figures XV(b), XVI(b) and XVII(b) respectively.

The graphical procedure again was that where any two piezometer tubes on one core recorded identical values of 'h_{s0}' - 'H' for any length of time, only the curve for the tube at the greatest "depth" was represented on the graphs for that time period.

(c) Correlation of 'h_{s0}' - 'H' with 'k'

With reasonably steady conditions existing in the cores during this experiment, the correlation between 'h_{s0}' - 'H' and 'k' for all three cores was high. Even in core I_2

(cont. pg. 132)

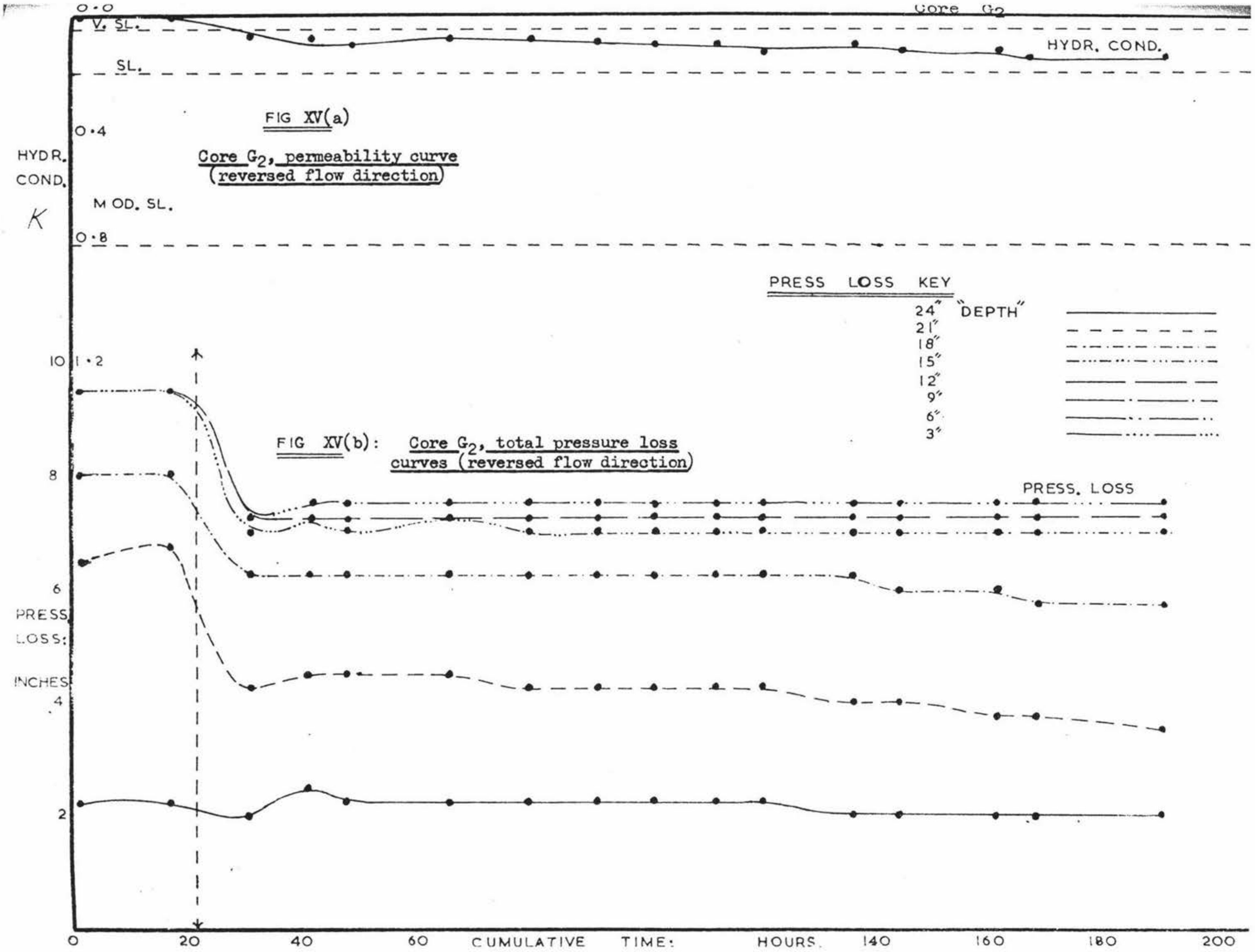


FIG XV(a)

Core G_2, permeability curve (reversed flow direction)

FIG XV(b): Core G_2, total pressure loss curves (reversed flow direction)

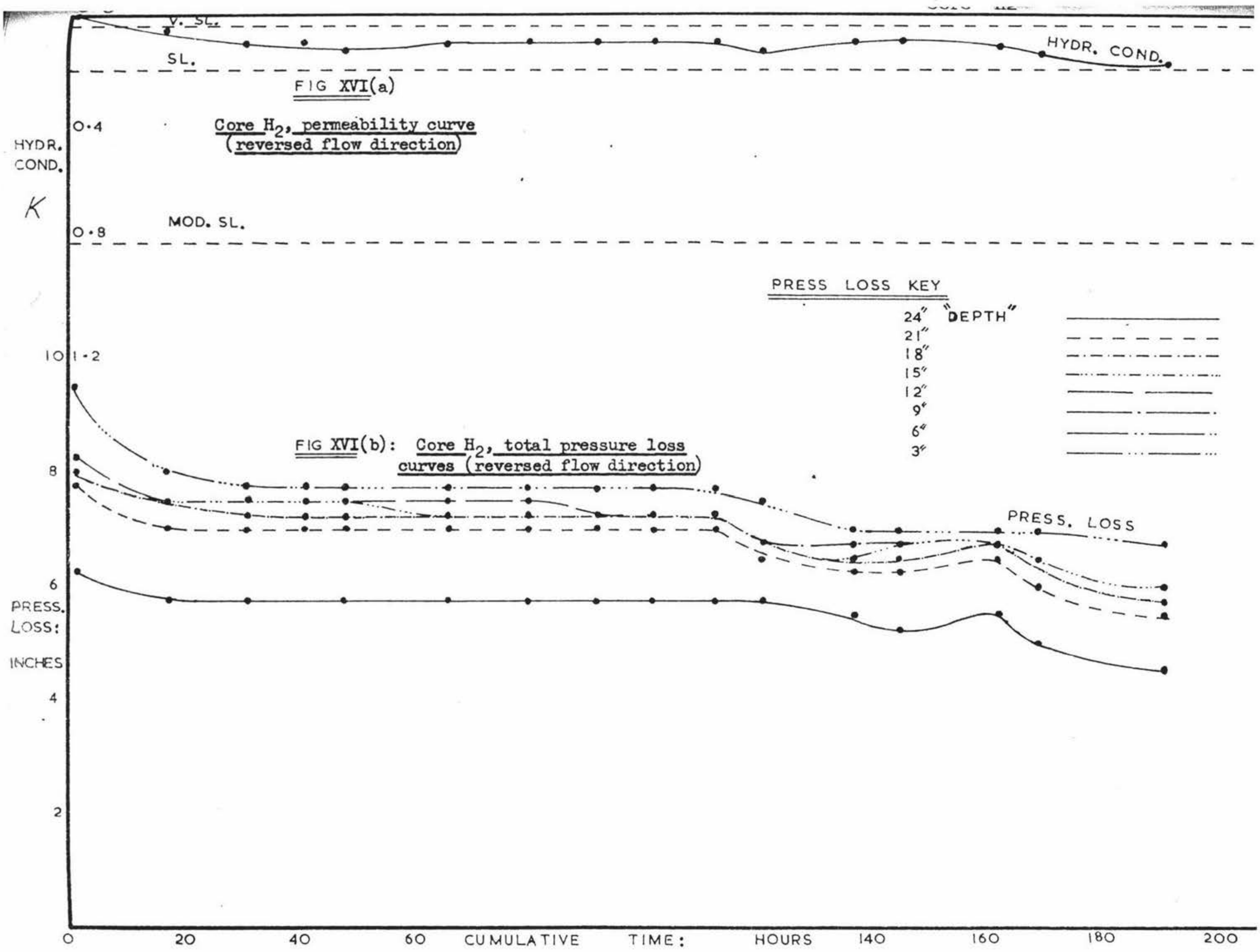


FIG XVI(a) Core H_2, permeability curve (reversed flow direction)

FIG XVI(b): Core H_2, total pressure loss curves (reversed flow direction)

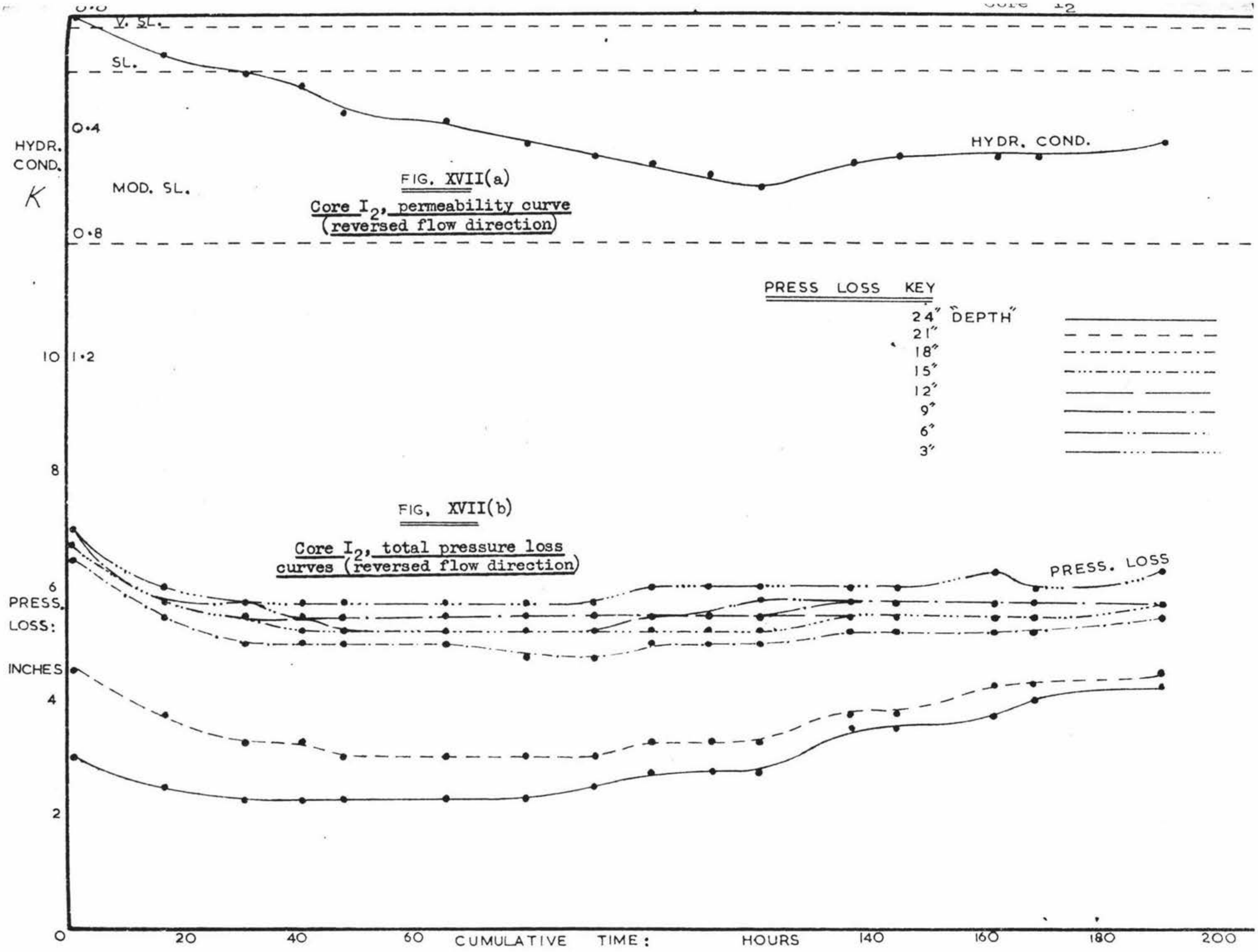


FIG. XVII(a)

Core I_2, permeability curve (reversed flow direction)

FIG. XVII(b)

Core I_2, total pressure loss curves (reversed flow direction) the increase and then levelling off of hydraulic conductivity with time followed a similar pattern to that of total pressure loss in each of the tubes.

(d) Examination of 'h_s' - 'H' Distribution within the Profile as a Basis for the Allocation of Relative Impedance Values to the Arbitrary 3 and 5 inch Layers

As with cores experiencing a normal flow direction, the hydraulic gradients that existed between any two piezometer tubes, reflected directly the frictional resistance to water flow of the 3 inch layer bounded on either side by the position of the tubes. Also, the hydraulic gradients that existed between the infiltrating surfaces or effluent ejection tubes and their nearest piezometer tubes, reflected directly the frictional resistance to water flow of the 5 inch or 3 inch layers between these points respectively. Hydraulic gradients were calculated in an identical manner to that outlined in subsection IV(d) above.

Below, in Tables XI(a), XII(a) and XIII(a), are listed the mean hydraulic gradients computed from sets of data for each piezometer tube of each core. The sets of data represent values taken at 13 time intervals between 41.5 accumulated hours and 191.5 hours (inclusive). The statistically computed standard errors of the means are also indicated. The arbitrary choice of the 13 time intervals listed (Appendices XIV, XV and XVI), was governed by the shape of the total pressure loss - cumulative time curves, and represented values taken where it was considered that the initial influence of reconnection and/or vacuum application had been largely dissipated.

As with the sand column and cores G_2, H_2, I_2, K_2 and L_2 under normal flow direction, the 0.1% level of probability was selected as a suitable basis on which to determine significant and non-significant differences between the means of the hydraulic gradients across arbitrary 3 inch and 5 inch layers. The difference for significance at 0.1% probability was 3.92.

Tables XI(b), XII(b) and XIII(b) list values of relative impedance. These values were computed from the mean gradients, taking the highest value for the three cores (viz. 1.10, being the gradient between 29 inches "depth" and 24 inches "depth" in core H_2) as an arbitrary value. The values, being relative, have no units, and individual values for each layer are given. Where any number of layers in one core were found to have mean gradients not significantly different, the relative impedance was computed from an overall mean value of the means of these particular layers.

In Figure XVIII, each horizon was assigned a relative impedance value, and the "depth" boundaries of the horizons are indicated. Consequently, convenient recognition of that horizon (or those horizons) which exhibited the least permeability is possible.

(cont. pg. 135)

"Depth" boundaries of layers	29"-24"	24"-21"	21"-18"	18"-15"	15"-12"	12"-9"	9"-6"	6"-3"	3"-0"
Mean hydr. gradient	0.43	0.66	0.67	0.30	0.070	0.00	0.013	0.077	0.083
S.E. of mean	±0.0087	±0.019	±0.017	±0.018	±0.0087	±0.000	±0.0086	±0.0084	±0.000

TABLE XI(a)

Mean hydraulic gradients of the arbitrary layers of core G_2
(reversed flow direction)

"Depth" boundaries of layers	29"-24"	24"-21"	21"-18"	18"-15"	15"-12"	12"-9"	9"-6"	6" - 3"	3"-0"
Mean hydr. gradient	1.10	0.37	0.083	0.032	0.013	0.0064	0.019	0.12	0.11
S.E. of mean	±0.022	±0.019	±0.000	±0.012	±0.0086	±0.0032	±0.01	±0.016	±0.037

TABLE XII(a)

Mean hydraulic gradients of the arbitrary layers of core H_2
(reversed flow direction)

"Depth" boundaries of layers	29"-24"	24"-21"	21"-18"	18"-15"	15"-12"	12"-9"	9"-6"	6"-3"	3"-0"
Mean hydr. gradient	0.60	0.17	0.52	0.096	0.026	0.051	0.0064	0.11	0.60
S.E. of mean	±0.040	±0.022	±0.034	±0.0091	±0.011	±0.012	±0.0032	±0.012	±0.017

TABLE XIII(a)

Mean hydraulic gradients of the arbitrary layers of core I_2
(reversed flow direction)

As noted in subsection IV(d) above, no quantitative comparisons <u>between</u> the three cores, G_2, H_2 and I_2, will be considered, due to the lack of sufficient replications to render any such comparisons valid. Similarly, because the respective relative impedances have different unity values, and because of the lack of vegetation on the infiltrating surfaces of reversed cores, no quantitative comparisons will be made between relative impedance values obtained from the experiments with a normal flow direction, and those obtained with the flow direction reversed. However, as pointed out previously, qualitative comparison of the <u>location</u> of the least, most, and intermediate impedance horizons will be made between cores and experiments by reference to the alphabetical letters assigned to each horizon in each core in each experiment. In all cases, the layer of least permeability is represented by 'A', the next by 'B', and so on.

"Depth" boundaries of layers	29"-24"	24"-21"	21"-18"	18"-15"	15"-12"	12"-9"	9"-6"	6"-3"	3"-0"
Relative impedances (R.I.)	0.39	0.61	0.61	0.27	0.070	0.0064	0.0064	0.070	0.070

TABLE XI(b)

Relative impedances of the arbitrary layers of core G_2
(reversed flow direction)

"Depth" boundaries of layers	29"-24"	24"-21"	21"-18"	18"-15"	15"-12"	12"-9"	9"-6"	6"-3"	3"-0"
Relative impedances (R.I.)	1.00	0.34	0.090	0.016	0.016	0.016	0.016	0.090	0.090

TABLE XII(b)

Relative impedances of the arbitrary layers of core H_2
(reversed flow direction)

"Depth" boundaries of layers	29"-24"	24"-21"	21"-18"	18"-15"	15"-12"	12"-9"	9"-6"	6"-3"	3"-0"
Relative impedances (R.I.)	0.52	0.13	0.52	0.067	0.015	0.067	0.015	0.13	0.52

TABLE XIII(b)

Relative impedances of the arbitrary layers of core I_2
(reversed flow direction)

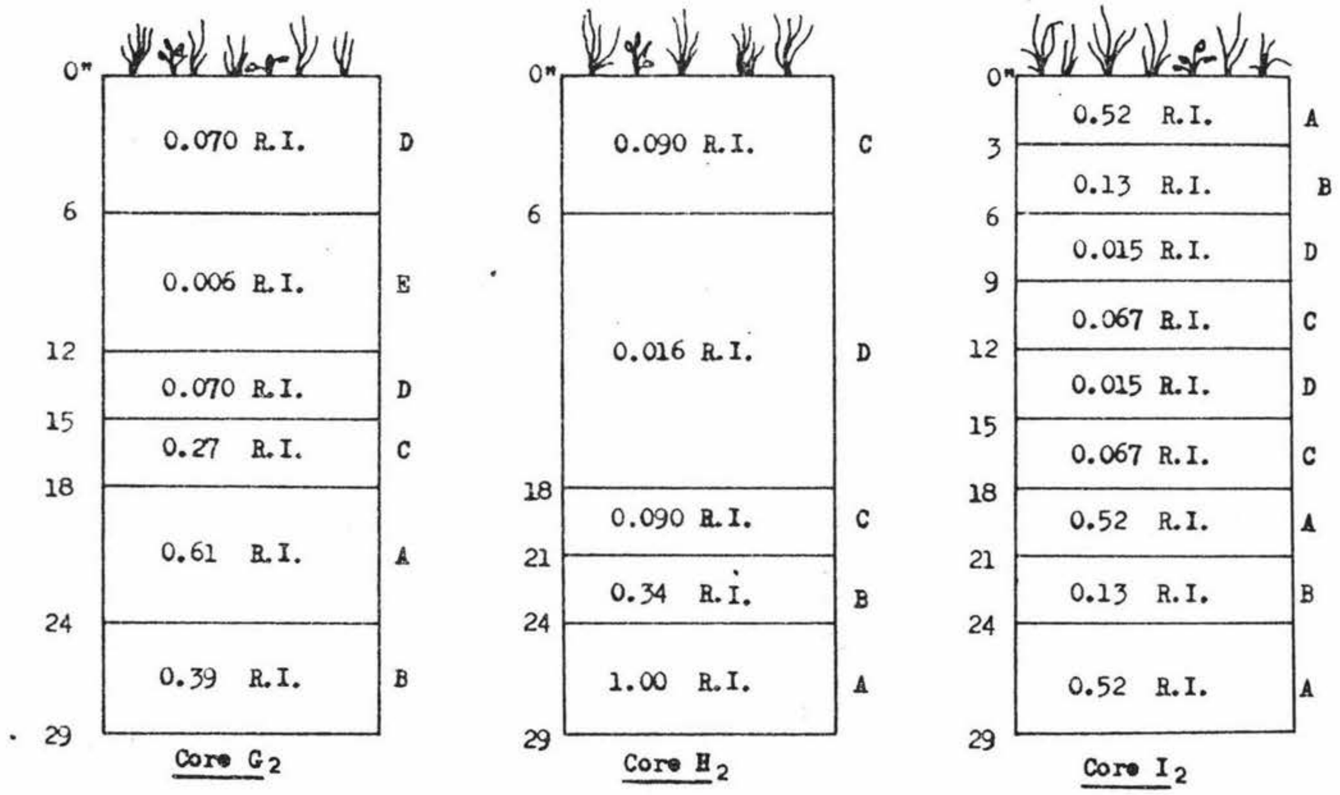


FIG. XVIII

The theoretical profiles of cores G_2, H_2 and I_2 (reversed flow direction)

VI MEASUREMENT OF THE RATE OF RISE OF 'H' IN INDIVIDUAL PIEZOMETER TUBES

The predetermined distance of rise in each tube was from 'H' = 1 inch to 'H' = 2 inches. This arbitrary choice was governed by the fact that the smallest 'H' recording in any tube prior to the experiment was 2 inches. As the rate of rise in any one tube was directly proportional to the overall hydraulic gradient between the surface and the tube being tested, the velocity of ascent of the meniscus in the tube was an exponential function of time.

Below, in Table XIV, are listed the time intervals (in seconds) for a 1 inch rise in all tubes in cores G_2, H_2, I_2, K_2 and L_2. These tests were performed with the flow direction reversed in the cores.

"Depth" position of tubes	24"	21"	18"	15"	12"	9"	6"	3"
Core G_2	53secs.	151secs.	180secs.	126secs.	160secs.	110secs.	240secs.	2500secs.
Core H_2	43	60	17	37	61	35	157	4200
Core I_2	21	29	26	25	40	48	21	40
Core K_2	1	3	7	11	21	10	16	380
Core L_2	3	5	7	6	6	7	27	29

TABLE XIV

Time rate of rise of 'H' in individual piezometer tubes

As can be seen from the Table, attempts to measure flow rate in this manner, by nature of the localised effects produced by the positioning of the piezometer tubes, was unsatisfactory. The occurrence of the situation within a core of recording a greater flow rate from a "deep" point in the soil than from one at a "shallower" point is indicative of the effect this technique had of recording only the resistance of the soil immediately adjacent to the tube opening. Stream lines leading from within the core to a tube base would have followed basically those indicated in Figure XIX (for a homogeneous medium), and would have congregated at the tube opening, thus producing a high current density at that

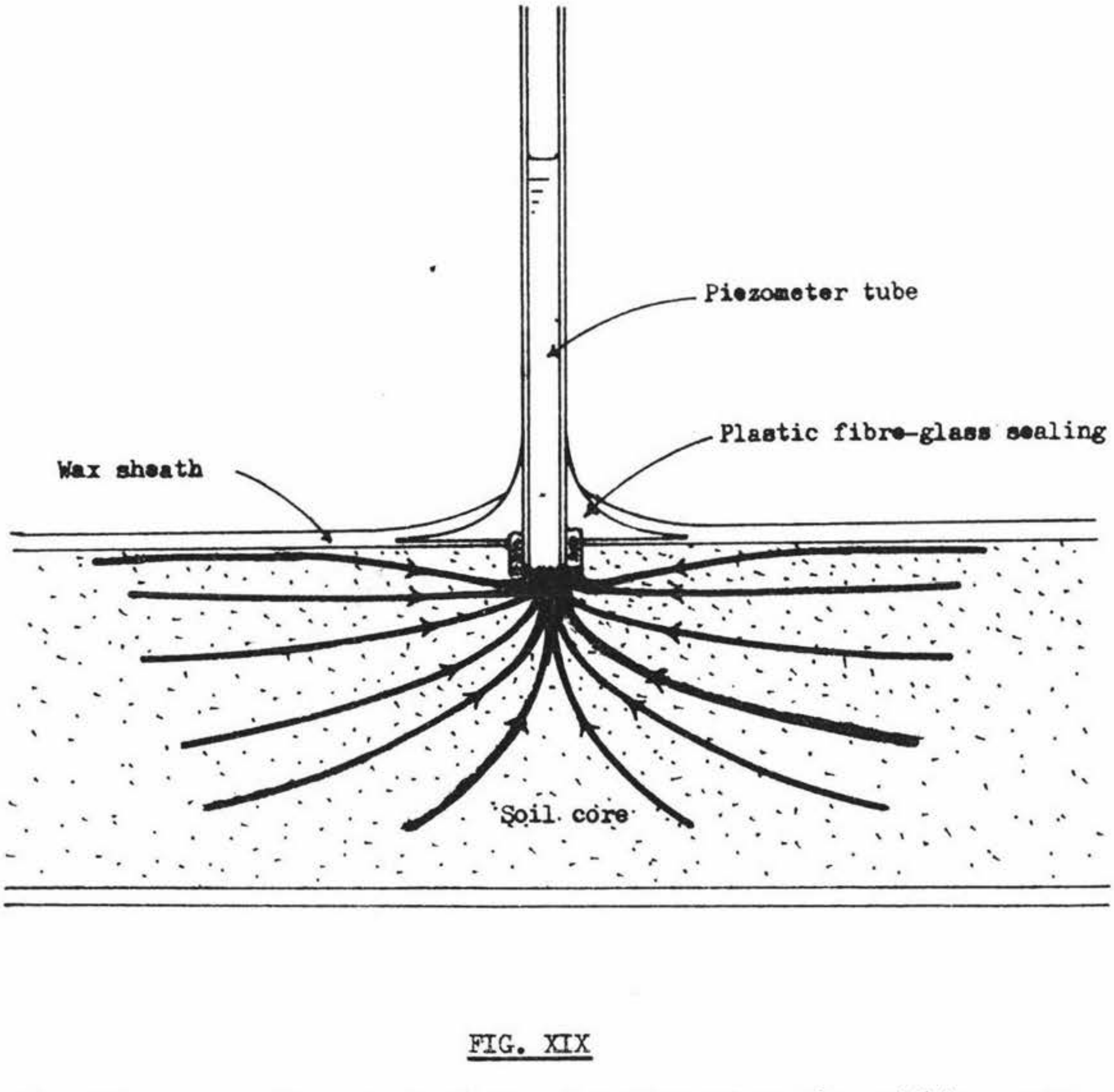


FIG. XIX

Possible stream lines to the base of a piezometer tube, within a core point. Such a high current density would have been present only within a small area (perhaps a few mms. in extent) around the tube base, because at greater distances from the base, stream lines would have tended to diverge, thus reducing the current density at any one point. The heterogeneity of the soil as a conducting medium would not have changed the basic pattern of stream lines leading to a tube opening, but may have caused divergence from the idealized pattern suggested by Figure XIV over small isolated areas of the porous soil body. Nevertheless, with a high current density at the tube bases, the quantity of water passing into any one tube per unit time would have been entirely dependent on the resistance of the tiny portion of soil actually in contact with the guaze on the tube base opening. Thus, if such a small portion of soil exhibited a high impedance, a relatively slow rise rate would have been recorded in the tube, largely irrespective of the overall impedance of the core down to that point. Similarly, if the small portion of soil was particularly pervious, because of the negligible volume of water necessary to fill the tube for 1 inch of its length in relation to the volume of the core, a rapid entry of water into the tube would have been recorded, again largely unaffected by the overall impedance of the core down to this point.

VII INDIRECT ASSESSMENTS OF INTRINSIC PERMEABILITY, BASED ON LABORATORY EXAMINATION OF CERTAIN PHYSICAL CHARACTERISTICS OF "UNDISTURBED" SOIL CORES

The physical soil characteristics examined were:-

(a) Structure - from the recommendations of O'Neal (1949), special emphasis was put on seeking information regarding the ratio of the length of the vertical and horizontal axes of structural units, the degree of overlap, and direction of easiest natural fracture.

(b) Visible porosity in both the vertical and horizontal planes.

(c) Compaction and consistency based on penetrometer readings and subjective analysis.

(d) Texture based on subjective analysis by feel, and laboratory mechanical analyses.

For convenience of comparison of results with those obtained from hydraulic tests on the cores, having identified the natural horizon boundaries, the analyses took the form of inspection of arbitrary 3 inch and 5 inch layers corresponding to those of the waxed samples tested directly for hydraulic conductivity.

(a) Structure (abstracted from Appendix II)

Below, in Table XV, is listed the structural development as it was assessed in the laboratory. It is noteworthy that very little structural development was identified in the bulk of the profile, so that the influence on permeability of such factors as degree of overlap, direction of easiest fracture, and horizontal and vertical axes ratios would be expected to be small.

Depth boundaries of layers	Comments
0" - 3"	Very weakly developed fine crumb structure in immediate vicinity of grass roots. Some cast granular structure tightly embedded in the soil matrix. No overlapping structural units detectable.
3" - 6"	Fairly tightly packed matrix with a little cast granular structure. Worm channels quite evident. No overlapping structural units detectable.
6" - 9"	Majority of soil matrix fairly tightly packed. Numerous cast granular structures. No overlapping structural units detectable.

(cont.)

(cont.)

Depth boundaries of layers	Comments
9" - 12"	Majority of soil matrix fairly tightly packed. Quite numerous cast granular structures. No overlapping structural units detectable.
12" - 15"	Cast granular structures not quite so strongly developed. No overlapping structural units detectable.
15" - 18"	Little structural development at all. Possibly some vestigial cast granular structures having arisen from burial by successive flood deposits. No overlapping structural units detectable.
18" - 21"	Little structural development. Again some vestigial cast granular structures. The bulk of the matrix is tightly packed. No overlapping structural units detectable.
21" - 24"	Quite distinct vestigial cast granular structures. Otherwise as for 18" - 21". No overlapping structural units detectable.
24" - 29"	Quite distinct vestigial cast granular structures. Slight tendency towards weakly developed, medium size prismatic structures.

TABLE XV

Structural development evident in a sample from the Ongley Park profile

Structure, then, can be expected not to have had a great influence on the differential intrinsic permeability values of the horizons. However, the overall lack of strongly developed structure itelf can be expected to have contributed to the relatively low conductivity at all depths.

(b) Visible Porosity (abstracted from Appendix II)

As can be seen from Table XVI below, horizontal intrinsic permeability below 12 - 15 inches could be expected to increase slightly as the result of a greater occurrence of horizontal porosity. However, in the vertical plane, there was no noticeable increase or decrease in the number of visible pores in any natural horizon or arbitrary layer. Hence, the effect of porosity on differential vertical conductances was not expected to be great.

Depth boundaries of layers	Visible pores
0" - 3"	Some visible pores created by passage of plant roots
3" - 6"	Considerable visible porosity
6" - 9"	Considerable visible porosity
9" - 12"	Considerable visible porosity
12" - 15"	Considerable visible porosity in vertical and horizontal directions
15" - 18"	Considerable visible porosity in vertical and horizontal directions
18" - 21"	Considerable visible porosity in vertical and horizontal directions
21" - 24"	Considerable visible porosity in vertical and horizontal directions
24" - 29"	Considerable visible porosity in vertical and horizontal directions

TABLE XVI

Visible porosity evident in a sample from the Ongley Park profile

(c) Compaction and Consistency (abstracted from Appendices I(b) and II respectively)

Table XVII lists the spring loading data obtained with a spring penetrometer applied to the sample of the Ongley Park profile. Relative compaction values were calculated, taking the highest mean spring loading reading (4.50 kgm.) as an arbitrary unity. Because readings were to be eventually reduced to relative values, no great importance was attached to absolute spring load values, especially since the needle used was not a standard accessory supplied by the manufacturers.

Depth boundaries of layers	0"-3"	3"-6"	6"-9"	9"-12"	12"-15"	15"-18"	18"-21"	21"-24"	24"-29"
Mean penetrometer readings (cms.)	4.1	4.8	4.7	4.7	4.8	7.0	3.3	5.7	7.8
Spring loading (krgms.)	2.60	3.00	2.95	2.95	3.00	4.10	2.25	3.45	4.50
Relative compaction	0.58	0.67	0.66	0.66	0.67	0.91	0.50	0.73	1.00

TABLE XVII

Relative compaction data obtained from a sample of the Ongley Park profile

The above data were supported by subjective assessments of consistency. All 3 and 5 inch layers, except 9 -12 inches, 12 - 15 inches and 15 - 18 inches were classified as "firm". The three layers not classified thus, were judged to be "friable". From study of the compaction and consistency data, one would have expected such a profile to exhibit the greatest impedance to water flow at depths below 15 inches, with perhaps the greatest impedance at about the 24 inch layer, and the least at the surface and underlying layers down to 15 inches.

The occurrence of an apparently uncompacted layer at 18 - 21 inches was inconsistent with the texture and consistency assessments, and suggested the possibility that the penetrometer needle may have been probing in or around a localised "soft spot" caused by organism channels, or buried organic matter. On the other hand, had there been previous burial of a surface layer by successive flood deposits (as suggested from structural examination), the 18 - 21 inch layer may well have included the previous surface layer, which would have been relatively well supplied with organic matter, and possibly not as tightly packed as other layers.

(d) Texture (abstracted from Appendices I(a) and II)

Table XVIII lists the textural classes assigned to each of the 3 inch and 5 inch layers of the core.

Depth boundaries of layers	Texture
0" - 3"	Silt loam
3" - 6"	Silt loam
6" - 9"	Very fine sandy loam
9" - 12"	Very fine to fine sandy loam
12" - 15"	Very fine sandy loam, bordering on a silt loam
15" - 18"	Silty clay loam
18" - 21"	Silty clay loam
21" - 24"	Silty clay loam
24" - 29"	Silty clay loam

TABLE XVIII

Textural classes of a sample of the Ongley Park profile

Tabled below are the mechanical analyses data of two other Ongley Park profiles, sampled from an area in close proximity to that from which cores G_2, H_2, I_2, J_2, K_2 and L_2 were extracted. These data represent the mean values compiled from two replicate determinations.

Depth	at 3"	at 6"	at 9"	at 12"	at 18"	at 24"
Coarse sand	0.46%	0.40%	1.59%	0.34%	0.35%	0.39%
Fine sand	58.95	63.12	70.51	69.78	64.67	58.18
Silt	18.28	21.66	13.82	17.66	20.08	27.62
Clay	20.65	15.54	15.62	14.96	16.88	16.10
Loss on solution	0.83	0.63	0.34	0.39	0.32	0.39
Loss on ignition	5.82	4.86	3.02	3.30	3.54	3.11
	104.99	106.21	104.90	106.43	105.84	105.79

TABLE XIX

Mechanical analysis of a sample of the Ongley Park profile

The apparently high relative percentages of fine sand from 6 inches down to 15 or 18 inches suggested less impedance to water flow in this region, while the occurrence of the highest quantities of coarse sand near the surface was indicative that a permeability restriction was unlikely to be consistently located at or near the surface.

Silt and clay fractions both appeared to be reduced in quantity about the "central depths", 6 or 9 inches down to 12 or 15 inches. This added support to the compaction, consistency and subjective textural observations, in suggesting that this "central" area would be expected to exhibit the least restriction to water flow.

VIII A QUALITATIVE ACCOUNT OF RESULTS OBTAINED FROM PREVIOUS* HYDRAULIC TESTS PERFORMED ON SOIL CORES FROM THE ONGLEY PARK PROFILE

Specifications of the experimental conditions for the testing of the four batteries of six cores each, were as listed below:-

Core identifications :	A_1, B_1, C_1, D_1, E_1, F_1; G_1, H_1, I_1, J_1, K_1, L_1; M_1, N_1, O_1, P_1, Q_1, R_1; S_1, T_1, U_1, V_1, W_1, X_1;
Dimensions of cores :	All cores were 30 inches long, with an infiltrating surface area of approximately 6 sq. inches .
Permeating liquid :	Tap water.
Liquid supply :	Overflow reservoir.
Flow direction :	Normal.
Static surface head :	Zero for cores A_1, B_1, C_1, D_1, E_1 and F_1 9.5 inches of water for the first three named of each of the three remaining batteries of cores 9.25 inches of water for the last three named of each of the three remaining batteries of cores.
Hydraulic head at core effluents :	30 inches of water for cores A_1, B_1, C_1, D_1, E_1 and F_1 1.75 inches of water for the 18 remaining cores named above.
Overall hydraulic gradients :	Unity for those cores experiencing a zero head 0.27 for those cores experiencing a 9.5 inch surface static head 0.26 for those cores experiencing a 9.25 inch surface static head.
Control of soil organisms :	Continual U.V. light treatment of the vegetative surfaces of all cores.

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* All records of data obtained from the testing of these 24 cores were destroyed by fire.

Temperature	:	Controlled air temperature at either $68 \pm 2^{\circ}F$ or $70 \pm 2^{\circ}F$.
Approximate soil moisture contents at initiation of the experiments	:	Slightly less than field capacity.
Nomenclature	:	Not applicable

The drop of the static surface head with distance from the reservoir has been previously discussed in subsection IV.

As data from the individual permeability and percolation experiments had not been statistically analysed or resolved to values of relative impedance before the loss of the raw data, only qualitative trends can be reported here. The trends, apparent from the study of the abovenamed cores, will be considered under the following headings:-

(a) Trends Apparent from Percolation Studies of Samples of the Ongley Park Profile

It became apparent during this experiment (concerning cores A_1, B_1, C_1, D_1, E_1 and F_1) that a layer of relatively high impedance was present at or about the mid-section of the cores (i.e. approximating the 15 inch depths). However, all piezometer tubes below this level (with these cores, tubes were inserted at 3, 6, 9, 12, 18 and 24 inch depths) failed to indicate any hydraulic head at all. It was considered, therefore, that while the percolation technique had identified the least permeable layer as being between 12 - 18 inches, by virtue of the fact that underlying layers thus never became "saturated", no indication of the conducting power of the lower half of the core was possible. Hence, the only conclusions drawn from such percolation studies was that the layer of greatest impedance was bounded by the tubes at 12 and 18 inches, and that there was also a reasonable impedance, noticeable in most cores, over the top 3 inches of the core.

It was because of the lack of information obtainable from horizons underlying the least permeable layer, that all subsequent experiments were performed with the cores mounted horizontally, and where precautions were taken to ensure that all horizons became "saturated" during the course of the experiment.

(b) Trends Apparent from Permeability Studies of Samples of the Ongley Park Profile, Mounted in Horizontal Positions

With one battery of cores (viz. M_1, N_1, O_1, P_1, Q_1 and R_1), the least permeable horizon appeared to be bounded by the positions of the 18 and 24 inch tubes (again, with all these tests, tubes were inserted at 3, 6, 9, 12, 18 and 24 inch depths). In the other two batteries, as with the percolation experiments reported above, an area between 12 and 18 inches appeared to be the most restricting. It was possible also with this technique to identify the next highest relative impedance layer, and this appeared to alternate between cores, and between batteries of cores, from being located in the top 3 inches, and the 18 - 24 inch subsoil layer. Almost invariably, the least impervious layer was located between 6 and 12 inches.

It is stressed that all results reported in subsection VIII above are derived from the author's memory, as unfortunate circumstances resulted in the destruction of all quantitative records. However, it is felt that the apparent trends, when considered together with the quantitative data subsequently obtained, will assist in the discussions and conclusions drawn concerning the problem and techniques of investigation.

SECTION F

GENERAL DISCUSSION AND CONCLUSIONS

I General Considerations of Sampler Designs

While the principle involved in the design of the sampler described is not a new one, there are several features incorporated which were not included in the designs reported by other workers. These features include:-

(a) The soil cutting ring is equipped with stabilizing wings. As the cutting ring also locks into the lower end of the inner tube, the benefit of the stabilizing wings is extended to this component. Thus their presence greatly assists the function of the thrust bearing.

(b) The bevel of the soil cutting ring overlaps the lower edge of the head, thus eliminating the possibility of pulverized material becoming wedged between the two components.

(c) Because of the inner tube design, transference of the cores to their semi-cylindrical transporting moulds is quickly and safely accomplished, and avoids the meticulous care needed when cores are slid lengthwise out of the inner tube. The transporting moulds themselves are unique and extremely well suited to their adapted roll.

Additionally, for the purpose of extracting 3 ft. long cores, the cost, weight and bulk of the machine are far less than the comparable machines of Kelley et al (1947) or Wells (1959), and are bettered in part only by the recent design of Starodumov (1962).

With minor modifications, the machine could be easily attached to a "Landrover" vehicle for the purpose of sampling from soils at widely differing geographical locations.

II General Considerations of the Laboratory Treatment of Cores prior to Percolation or Permeability Experiments

The various methods reported in the literature on desirable encasement of cores, invites some comment. It was the author's experience that an encasing agent that is applied in liquid form, and which later solidifies, is an ideal encasement, as it conforms to the micro-shape of the core periphery. Paraffin wax is considered to provide a suitable encasing medium, though the lack of inherent strength of the material can be a problem. It is felt that perhaps the most desirable encasement is a combination of a conforming medium surrounded by a more stable metal or plastic cylinder. As an instance of this technique, Reeve and Luthin (1957) used a bentonite slurry as the conformer and a plastic cylinder surrounding it to provide rigidity. It is felt also that, if desired, wax could be substituted for the bentonite slurry with similar effectiveness, and, in fact, the technique employed by the author utilized a conforming wax sheath partly surrounded by a rigid cardboard mould. Metal or rigid cylinder containers alone are considered to be unsuitable when cores are required for permeability studies, as either some lateral compaction of the core is unavoidable if an adequate seal between core and cylinder is to be made, or channelling between the core and the casing will occur if lateral compaction of the core is avoided. The application of a small quantity of wax seal around the top edge of the core and the rigid cylinder (Taylor and Heuser 1953) is considered to be of doubtful benefit, as immediately beneath the termination of the wax, water will still be able to travel relatively unrestricted between the core and the cylinder, unless the latter again is pressed tightly against the core.

An advantage of a wax encasement alone (or at least not completely surrounded by a rigid container) is that, because of the slight flexibility of the material, swelling of clay minerals within the core is not rigidly resisted. Soil cores contained within tightly fitting rigid containers can suffer exaggerated effects of the swelling tendencies of their clay minerals upon wetting. This will be especially so with montmorillinitic type clay minerals. With lateral swelling resisted, the end result will be an increased internal compression of the core, and the effects of this could be far reaching with permeability studies.

Any technique which entails the testing of the core retained within the cylinder used to form and collect it (Lutz 1947, Steinbrenner 1950), must make the basic assumption that each core is, in fact, "undisturbed" as adequate visual examination is not possible. It was the author's experience that even with short cores, such an assumption can be dangerous because it is quite possible that the contained plug bears no structural resemblance to the profile from which it is extracted. Similarly, the possible inclusion of large stones etc. can not be detected without some visual examination of the core prior to encasement.

III General Considerations of Hydraulic Conductivity Investigations Utilizing "Undisturbed" Soil Cores

The general hydraulic investigation approach, incorporating pressure differential analyses, was shown to be well grounded by the results obtained from the sand column experiment. Comparison of the theoretical and actual profiles (Fig. VIII) demonstrates the effectiveness of the method (even with widely spaced piezometer tubes) in locating the horizons of varying impedance. The advantages of this approach over direct measurements of flow rate into each piezometer tube were also demonstrated. It was found that unlike these particular flow rate determinations, the recording of pressure heads in individual tubes is largely unaffected by localised impedance in the vicinity of the tube base (Fig. XIX). The only effects such localised impedance can have on pressure indications is in the time taken for individual tubes to reach equilibrium with the static head applied to the infiltrating surface. This latter phenomenon is not of paramount importance, however, due to the relatively slow rate of overall pressure changes in the profile once the initial settling down period has been fulfilled.

It is suggested, however, that use could be made from an appreciation of the distribution of stream lines in a core to locate localised pervious or impervious material by insertion of a hypodermic needle into the waxed core at many points. The flow rate recorded from the needle at any one point in the core, would be indicative of the impedance of the small area of soil immediately adjacent to the needle inlet opening. It is also noteworthy that difficulty might be encountered through micro-compaction effects produced by the insertion of the needle, but that with a very fine needle these effects could be largely overcome. Such a procedure warrants further investigation, but it was not possible to explore the technique during the investigations reported herein.

Similarly, the pressure differential analysis has certain advantages over methods embodying the direct recording of flow rates from core effluents. These advantages are:-

(a) Some investigators (Slater and Byers 1931, Marsh and Swarner 1948, Schiff and Dreibelbis 1949) have noted the inherent lack of consistency between permeability values obtained from a number of relatively small diameter soil cores.

(b) The pressure differential studies are based on the relation between any two adjacent points in the profile, and such characteristics as variable surface impedance do not therefore affect the results.

(c) Any attempt to cut or break the profile into layers, to test directly the flow rate, is subject to the criticism that the influence of the infiltrating surface disturbance could be misleading.

(d) Relative impedance values derived from pressure differentials remain fairly constant, even while the overall permeability rate of the core changes markedly, unless of course, the change in 'k' is brought about by extreme conditions or mechanical failure of the core or its encasement.

There are also certain limitations with the pressure differential analysis technique:-

(a) The time and labour involved in sealing a number of piezometer tubes on to each core is far in excess of that necessary for straight permeability determinations, and could be a deterrent to the treatment of a large number of cores in this manner.

(b) Because of the impracticability of placing more than one tube at any one depth, pressure readings throughout the length a core are not replicated.

(c) Entrapped air in the pores and tubes can lead to false pressure readings.

(d) Pressure fluctuations in the short term are not always readily detectable.

(e) There is an inconsistent short term relationship between 'pressure loss - time curves' and 'hydraulic conductivity - time curves'.

(f) Even though heterogeneity of a particular arbitrary profile layer is less important than when measuring flow rates, occasionally the position of a worm channel can unduly influence the pressure readings in any one tube.

The overall hydraulic conductivity of each core must, however, be continually checked during differential pressure loss determinations, as sudden changes or abnormally high or low 'k' values serve as criteria to assist in the selection of valid and invalid pressure loss data.

It is thus concluded that results obtained from the pressure differential studies described herein, have shown that a satisfactory approach has been made in the identification of the least permeable horizon in a soil known to be characterized by low intrinsic permeability. It is suggested that more widespread use could be made of this type of approach in fundamental studies of soils exhibiting drainage problems of unusual difficulty. However, it is pointed out that with the limitations imposed by the experimental technique, attempts to differentiate soil layers, differing only slightly in relative impedance, are not warranted; nor would such differentiation be of much practical applicability in the field.

Recent work by Nakayama and Jackson (1963) suggests the possibility that future studies of fundamental drainage causes could incorporate certain isotopic tracers in the infiltrating water. It would appear from their work with tritiated water (THO) that saturated flow velocity determinations through successive arbitrary layers would be possible with labelled water. Such a technique could provide a large step forward in the identification of layers of varying permeability within a profile.

IV The Ongley Park Profile

Study of the theoretical profiles of cores G_2, H_2, I_2, K_2, and L_2 (Fig. XIV) reveals that without exception the high impedance layer was located below 18 inches. In two cases, it was confined to the 18 - 21 inch layer, and in another two, to the 21 - 24 inch layer, while the third spread the layer from 21 to 29 inches. It is noteworthy that in almost all cases, the relative impedance value of the 'A' layer was well in excess of the 'B' value for the same core, but that 'B' was seldom as largely separated from 'C' as it was from 'A'. It is also noteworthy that in two cores the surface 3 inches exhibited the second highest impedance, and that in two of the three remaining cores, it was classed as the third highest of the relative impedance values assigned to those cores. The lowest and second lowest impedance layers were generally located between 3 inches and 18 inches depth, except that in two cores they extended down to 21 inches, and in another core they extended, instead, to the vegetative surface.

As a final check on the effectiveness of the technique, comparison of the theoretical profiles of cores G_2, H_2 and I_2 under reversed flow direction (Fig. XVIII) with the same cores under normal flow direction (Fig. XIV) reveals that the reproducibility of results was quite good in cores G_2 and H_2 but was unexplainably poor in core I_2. With both normal and reversed flows, the 'A' impedance layers were located at about the same position in either one of the cores G_2 and H_2, although the thickness of the layers varied somewhat. In core I_2, however, although location of the greatest impedance layer was in both cases at 18 - 21 inches, with reversed flow, identical relative impedance layers were also located at the 0 - 3 inch and 24 - 29 inch layers - an almost complete reversal of the trend indicated with flow direction normal. Comparison of locations of the 'B', 'C', 'D' and 'E' magnitude layers between reverse and normal flow direction experiments, appears to be very inconsistent, and attempted identification of trends amongst these layers would not be very fruitful. However, when viewing all eight theoretical profiles together, location of the greatest impedance layer can be narrowed down to having been within an 11 inch layer from 18 - 29 inches almost without exception. There was a predominantly wide margin between the relative impedance values for this layer and any other relative impedance values within a particular core. Similarly, but with stronger reservations, it is concluded that the least impedance layer was situated between approximately 3 inches depth and 18 inches depth. Although there appears to be some considerable scatter of the location of intermediate layers, it must be remembered that the object of the experimental procedure was primarily to locate the <u>highest</u> impedance layer. To that end, the technique has proved successful, but any attempt to further define a number of other horizons, based on the evidence presented here, would be open to serious criticism. It will be noted, too, that the suggested location of the greatest impedance layer, as determined by this technique, is in keeping with the allocation of its position based on a combination of the indirect assessments considered previously. The location of the least impedance layer also conforms to the suggestions that become apparent from consideration of the indirect assessments.

Considering the quantitative relative impedance results with the qualitative trends noted from similar tests performed in previous experiments, it would appear that if there is a consistent band of highly impervious material in the Ongley Park area, it must vary considerably in depth of location. That this may, in fact, be the case is supported by the structural analysis data, which indicated the possibility of a buried soil, the surface of which appears to have been at about the 18 - 21 inch depth in the profile sample. There was also a slight increase in the "loss by ignition" (largely organic matter) at the 18 inch depth in the mechanical analyses of two samples of the profile. The high impedance layer, located by the pressure differential investigations (at 18 - 29 inches), coincides well with the increased relative compaction indicated by penetrometer readings of a sample from the same area. Bearing in mind that the previous twentyfour cores were obtained from different sampling sites in the Ongley Park area, it is therefore suggested that a relatively impervious compacted layer of silt loam is present throughout the profile. It is further suggested that this layer may represent the upper portion of a buried alluvial soil, and that its occurrence is at varying depths in the present profile. It is possible that this lack of uniform depth location has been caused by;

(a) topographical variations of the buried soil, and/or

(b) artificial levelling that has undoubtedly occurred on a recreational ground, such as Ongley Park.

The thickness of this layer appears to vary from 6 to 11 inches. The tendency of water to lie on the soil surface during winter appears, thus, to be a direct result of the inability of the wetting front to penetrate this particular layer at a rate sufficient to prevent backing up of the infiltrating water to the vegetative surface, rather than the result of general profile and/or surface impedance. For this theory to be acceptable, it is, however, necessary to postulate that lateral movement of water above the impeding layer is also insufficiently rapid to enable adequate movement to the pervious backfill of the existing tile drain trenches.

SECTION G

SUMMARY

A study was made of the fundamental characteristics of a selected soil exhibiting a poor drainage condition. In order to examine in the laboratory hydraulic properties of samples of the soil, a coaxial tube rotary soil sampler was developed, which overcame many of the difficulties noted by previous workers in this field.

Several critical tests were performed with the sampling apparatus to assess its effectiveness in extracting "undisturbed" soil cores.

A complete laboratory technique was evolved for the encasement and treatment of cores, in order that their flow rates and profile pressure distributions could be determined.

The pressure losses across arbitrary sized profile layers were statistically analysed and grouped under the convenient index of relative impedance.

Theoretical profiles, compiled from relative impedance data, were diagrammatically represented for each of five samples obtained from the soil at Ongley Park. The five theoretical profiles were compared with previous qualitative data obtained from twentyfour similar samples from different sites in the Park.

All relative impedance data were compared with qualitative indirect assessments of intrinsic permeability. These included a profile description, mechanical analyses, structural examination, compaction data, visible porosity and past and present field observations.

Several suggestions, based on the evidence collected, were put forward concerning the location and general history of the greatest impedance layer located in the Ongley Park profile.

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APPENDIX 1(a)

Mechanical analyses of two samples of the Ongley Park profile

Sample No. I

Depth	at 3"	at 6"	at 9"	at 12"	at 18"	at 24"
Coarse sand	0.12%	0.09%	0.14%	0.13%	0.50%	0.67%
Fine sand	52.04	56.93	59.66	60.89	74.52	65.03
Silt	17.43	21.14	18.54	26.19	15.40	21.95
Clay	27.06	23.34	22.00	16.85	12.16	14.02
Loss on solution	0.92	0.51	0.41	0.46	0.20	0.40
Loss on ignition	6.23	5.31	3.64	3.60	3.27	2.92
	103.80	107.32	104.39	108.12	106.05	104.99

Sample No. II

Depth	at 3"	at 6"	at 9"	at 12"	at 18"	at 24"
Coarse sand	0.80%	0.70%	3.14%	0.55%	0.19%	0.11%
Fine sand	65.85	69.31	81.36	78.67	54.81	51.32
Silt	19.12	22.17	9.09	9.12	24.76	33.28
Clay	14.24	7.73	9.24	13.07	21.59	18.17
Loss on solution	0.73	0.75	0.27	0.31	0.44	0.37
Loss on ignition	5.40	4.40	2.39	2.90	3.80	3.30
	106.14	105.06	105.49	104.62	105.59	106.55

APPENDIX 1(b)

Penetrometer scale readings at varying depths in a sample from the Ongley Park profile

Depth boundaries of layers	0"-3"	3"-6"	6"-9"	9"-12"	12"-15"	15"-18"	18"-21"	21"-24"	24"-29"
Reading No.									
1	3.9cms.	5.6cms.	4.5cms.	4.9cms.	3.5cms.	5.5cms.	4.8cms.	5.8cms.	7.9cms.
2	3.0	2.7	5.0	4.5	5.1	8.6	2.6	6.4	7.9
3	5.5	6.0	4.7	-	5.7	6.8	5.4	4.9	7.4
Mean scale reading	4.1	4.8	4.7	4.7	4.8	7.0	3.3	5.7	7.8

APPENDIX II

Description of the physical characteristics of the Ongley Park profile

The following description is of a single sample of the profile. Although not necessarily typical of the entire area, it did represent the general profile of the selected area from which samples G_2, H_2, I_2, J_2, K_2 and L_2 were extracted.

Depth boundaries of natural horizons

First	:	Surface to 6.5 inches depth
Second	:	6.5 inches to 16 inches depth
Third	:	16 inches to 26.5 inches depth

Arbitrary boundary divisions: 0"-3", 3"-6", 6"-9", 9"-12", 12"-15", 15"-18", 18"-21", 21"-24" and 24"-29"

Moisture condition : Just moist at all depths

Depth boundaries of layers	Colour (Munsel desc.)
0" - 3"	10YR, 4/2; dark grey brown
3" - 6"	10YR, 4/3; brown to dark brown
6" - 9"	2.5Y, 5/4; light olive brown
9" - 12"	2.5Y, 6/3 to 5Y, 6/3; pale olive to light yellowish brown
12" - 15"	2.5Y, 5/4; light olive brown
15" - 18"	2.5Y, 5/4; light olive brown
18" - 21"	2.5Y, 5/4; light olive brown
21" - 24"	2.5Y, 5/4; light olive brown
24" - 29"	2.5Y, 6/4 to 2.5Y, 5/4; light yellowish brown to light olive brown

(cont.)

APPENDIX II (cont.)

Depth boundaries of layers	Texture
0" - 3"	Silt loam
3" - 6"	Silt loam
6" - 9"	Very fine sandy loam
9" - 12"	Very fine to fine sandy loam
12" - 15"	Very fine sandy loam, bordering on a silt loam
15" - 18"	Silty clay loam
18" - 21"	Silty clay loam
21" - 24"	Silty clay loam
24" - 29"	Silty clay loam

Depth boundaries of layers	Consistency
0" - 3"	Firm
3" - 6"	Firm
6" - 9"	Friable
9" - 12"	Friable
12" - 15"	Friable
15" - 18"	Firm
18" - 21"	Firm
21" - 24"	Firm
24" - 29"	Firm

(cont.)

APPENDIX II (cont.)

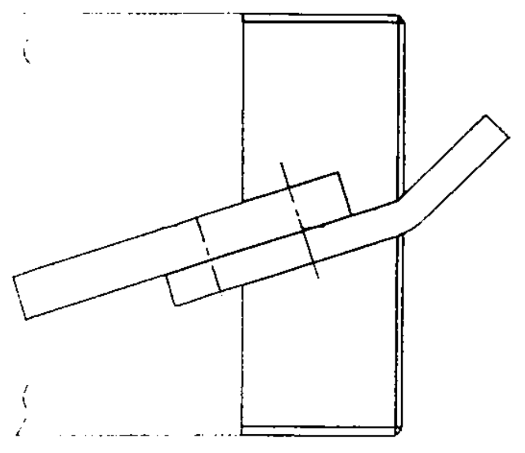
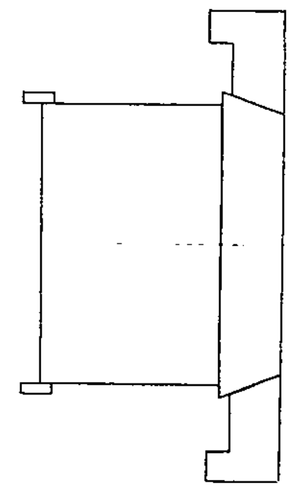
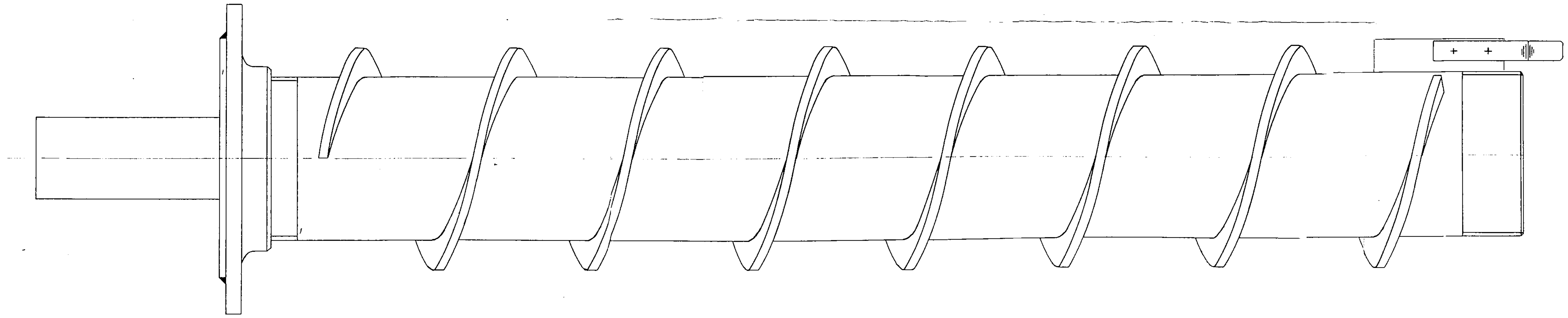
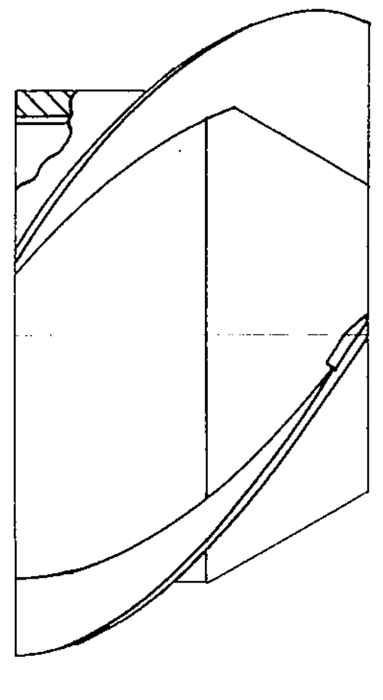
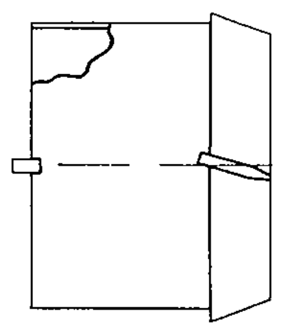
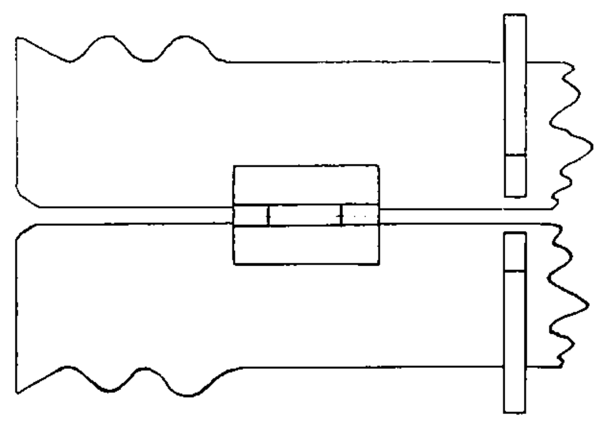
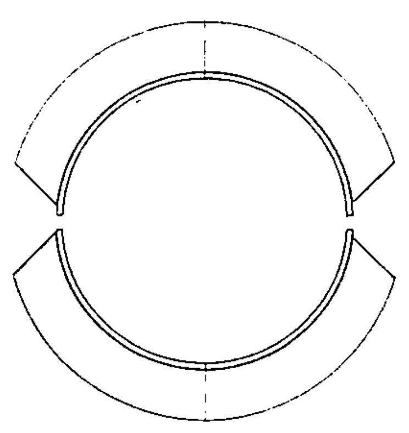
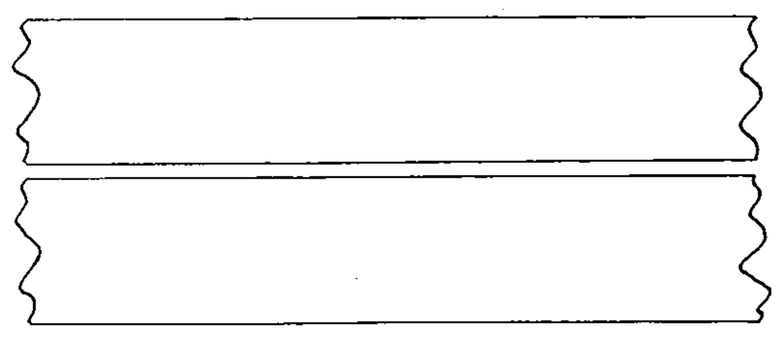
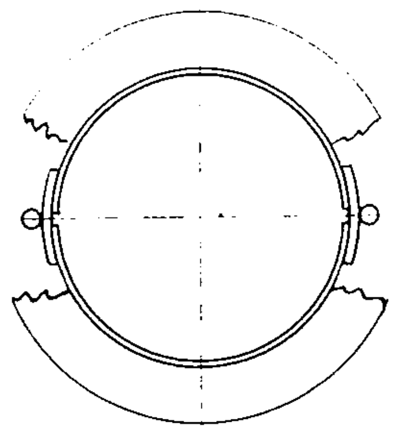
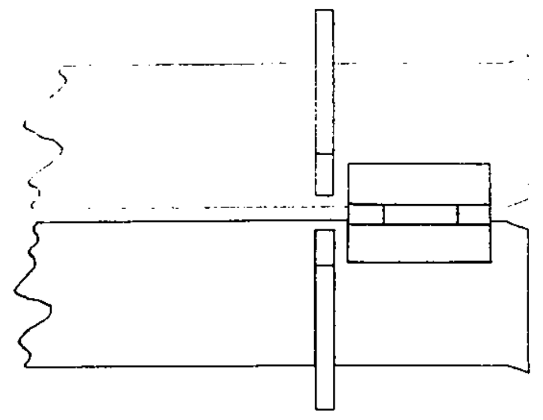
Depth boundaries of layers	Visible pores
0" - 3"	Some visible pores created by passage of plant roots
3" - 6"	Considerable visible porosity
6" - 9"	Considerable visible porosity
9" - 12"	Considerable visible porosity
12" - 15"	Considerable visible porosity in vertical and horizontal directions
15" - 18"	Considerable visible porosity in vertical and horizontal directions
18" - 21"	Considerable visible porosity in vertical and horizontal directions
21" - 24"	Considerable visible porosity in vertical and horizontal directions
24" - 29"	Considerable visible porosity in vertical and horizontal directions

Depth boundaries of layers	Structure
0" - 3"	Very weakly developed fine crumb structure in immediate vicinity of grass roots. Some cast granular structure tightly embedded in the soil matrix. No overlapping structural units detectable.
3" - 6"	Fairly tightly packed matrix with a little cast granular structure. Worm channels quite evident. No overlapping structural units detectable.
6" - 9"	Majority of soil matrix fairly tightly packed. Numerous cast granular structures. No overlapping structural units detectable.
9" - 12"	Majority of soil matrix fairly tightly packed. Quite numerous cast granular structures. No overlapping structural units detectable.
12" - 15"	Cast granular structures not quite so strongly developed. No overlapping structural units detectable.

(cont.)

APPENDIX II (cont.)

15" - 18"	Little structural development at all. Possibly some vestigial cast granular structures having arisen from burial by successive flood deposits. No overlapping structural units detectable.
18" - 21"	Little structural development. Again some vestigial cast granular structures. The bulk of the matrix is tightly packed. No overlapping structural units detectable.
21" - 24"	Quite distinct vestigial cast granular structures. Otherwise as for 18" - 21". No overlapping structural units detectable.
24" - 29"	Quite distinct vestigial cast granular structures. Slight tendency towards weakly developed, medium size prismatic structures.

APPENDIX IV

Flow rates from a capillary tube as they were affected by temperature

No temperature control

Interval between readings	Cumulative time (hrs.)	Day or night period	Max. or min. temperature	Volume of leachate (mls.)	Flow rate (mls./hr.)
8.25 hrs.	8.25	day	66°F	119.0	14.5
16.00	24.25	night	48	181.0	7.5
8.50	32.75	day	67	121.0	14.2
15.25	48.00	night	52	180.0	11.8
8.50	56.50	day	68	121.0	14.2
15.50	72.00	night	54	184.0	11.9
8.50	80.50	day	68	119.0	14.0
15.50	96.00	night	45	168.0	10.8
8.00	104.00	day	67	113.0	13.9
16.50	120.50	night	54	189.0	11.5
8.50	129.00	day	67	118.0	14.4
15.50	144.50	night	52	170.0	11.0
8.75	153.25	day	67	124.0	14.2
15.00	168.25	night	57	173.0	11.5

Controlled air temperature

Interval between readings	Cumulative time (hrs.)	Day or night period	Max. or min. temperature	Volume of leachate (mls.)	Flow rate (mls./hr.)
1.75 hrs.	1.75	day	67°F	25.0	14.3
15.75	17.50	night	67	225.0	14.3
8.50	26.00	day	67	119.0	14.0
15.50	41.50	night	67	221.0	14.3
7.25	48.75	day	67	105.0	14.5
18.00	66.75	night	67	255.0	14.2
14.00	80.75	day	67	197.0	14.1
11.25	92.00	night	67	158.0	14.1
10.75	102.75	day	67	155.0	14.4
11.00	113.75	night	67	157.0	14.4
8.00	121.75	day	67	117.0	14.6
15.75	147.50	night	67	225.0	14.3

(cont.)

APPENDIX IV (cont.)

Interval between readings	Cjmulative time (hrs.)	Day or night period	Max. or min. temperature	Volume of leachate (mls.)	Flow rate (mls./hr.)
8.25 hrs.	155.75	day	67°F	120.0	14.5
16.25	172.00	night	67	229.0	14.1

APPENDIX V

Total pressure loss and flow data from a percolation experiment with the sand column

Interval between readings (hrs.)	Cumulative time (hrs.)	Volume of leachate (mls.)	Percolation rate (mls./hr.)	Percolation rate (ins./hr.)	Hydraulic conductivity 'k' (ins./hr.)	Total pressure losses at each depth				
						at 3" depth (ins.)	at 6" depth (ins.)	at 12" depth (ins.)	at 18" depth (ins.)	at 24" depth (ins.)
0.50	0.50	960	1920	19.7	19.7	1.75	5.00	11.50	14.75	23.25
0.50	1.00	990	1980	20.3	20.3	1.75	5.00	11.50	14.50	23.25
0.50	1.50	1020	2040	20.9	20.9	1.75	5.00	11.50	14.50	23.00
0.50	2.00	1065	2130	21.8	21.8	1.75	5.25	11.50	14.50	23.00
0.50	2.50	1085	2170	22.2	22.2	1.75	5.25	11.50	14.50	23.25
0.50	3.00	1100	2200	22.5	22.5	1.75	5.25	11.75	14.50	23.25
1.25	4.25	2700	2160	22.1	22.1	1.75	5.25	11.75	14.50	23.25
0.50	4.75	1065	2130	21.8	21.8	1.75	5.25	11.75	14.50	23.25
0.50	5.25	1100	2200	22.5	22.5	1.50	5.00	11.75	14.50	23.25
0.50	5.75	1080	2160	22.1	22.1	1.50	5.00	11.75	14.50	23.25
0.50	6.25	1050	2100	21.5	21.5	1.50	5.00	11.75	14.50	23.25
0.50	6.75	1040	2080	21.3	21.3	1.50	5.00	11.75*	14.50	23.25
0.50	7.25	1050	2100	21.5	21.5	1.50	5.00	11.75*	14.50	23.25
4.25	11.50	8170	2022	20.7	20.7	1.25	4.00	11.00	14.00	22.75
12.00	23.50	-	-	-	-	1.25	3.25	9.50	12.50	21.50
1.00	24.50	2300	2300	23.6	23.6	1.25	3.25	9.50	12.50	21.50
1.00	25.50	2420	2420	24.8	24.8	1.25	3.25	9.25	12.50	21.25
1.00	26.50	2450	2450	25.1	25.1	1.25	3.25	9.25	12.50	21.25
1.75	28.25	3950	2257	23.1	23.1	1.25	3.25	9.25	12.50	21.25
1.00	29.25	2360	2360	24.2	24.2	1.25	3.25	9.25	12.25	21.25

(cont.)

APPENDIX V (cont.)

Interval between readings (hrs.)	Cumulative time (hrs.)	Volume of leachate (mls.)	Percolation rate (mls./hr.)	Percolation rate (ins./hr.)	Hydraulic conductivity 'k' (ins./hr.)	Total pressure losses at each depth				
						at 3" depth (ins.)	at 6" depth (ins.)	at 12" depth (ins.)	at 18" depth (ins.)	at 24" depth (ins.)
1.00	30.25	2390	2390	24.5	24.5	1.25	3.25	9.25	12.25	21.25
1.00	31.25	2390	2390	24.5	24.5	1.25	3.25	9.00	12.25	21.00
0.25	31.50	600	2400	24.6	24.6	1.25	3.25	9.00	12.25	21.00
16.00	47.50	-	-	-	-	1.25	3.25	7.75	10.75	19.75
1.25	48.75	2900	2320	23.7	23.7	1.25	3.25	7.75	10.75	19.75
1.00	49.75	2550	2550	26.1	26.1	1.25	3.25	7.75	10.75	19.75
1.00	50.75	2580	2580	26.4	26.4	1.25	3.50	8.00*	10.75	19.75
1.50	52.25	3940	2625	26.9	26.9	1.25	3.50	8.00	10.75	19.75
1.00	53.25	2585	2585	26.5	26.5	1.25	3.50	8.00	10.75	19.75
1.00	54.25	2590	2590	26.5	26.5	1.50	3.50	8.00	10.75	19.75
1.00	55.25	2620	2620	26.8	26.8	1.50	3.50	8.00	10.75	19.75
16.25	71.50	-	-	-	-	1.75	4.00	7.75	10.00	19.00
1.00	72.50	2900	2900	29.7	29.7	1.75	4.00	8.00*	10.00	19.00
1.00	73.50	2980	2980	30.5	30.5	1.75	4.25	8.00	10.00	19.00
1.00	74.50	3650	3650	31.2	31.2	1.75	4.25	8.25	10.25*	19.00
0.50	75.00	1570	3140	32.1	32.1	1.75	4.50	8.25	10.75*	19.00
1.25	76.25	3920	3140	32.1	32.1	2.00	4.25	8.25	10.25*	19.00
1.00	77.25	2960	2960	30.3	30.3	1.75	4.25	8.25	10.25	19.00
1.00	78.25	3080	3080	31.5	31.5	1.75	4.25	8.25	10.25	19.00
1.00	79.25	3020	3020	30.9	30.9	2.00	4.25	8.25	10.25	19.00
17.50	96.75	-	-	-	-	2.25	5.25	10.00*	12.75*	20.00
46.75	143.50	-	-	-	-	2.75	6.00	11.50	13.75	22.25
1.00	144.50	3860	3860	39.5	39.5	2.75	6.00	11.50	14.00	22.25

(cont.)

APPENDIX V (cont.)

Interval between readings (hrs.)	Cumulative time (hrs.)	Volume of leachate (mls.)	Percolation rate (mls./hr.)	Percolation rate (ins./hr.)	Hydraulic conductivity 'k' (ins./hr.)	Total pressure losses at each depth				
						at 3" depth (ins.)	at 6" depth (ins.)	at 12" depth (ins.)	at 18" depth (ins.)	at 24" depth (ins.)
1.00	145.50	3910	3910	40.0	40.0	2.75	6.00	11.50	14.00	22.25
1.00	146.50	3930	3930	40.2	40.2	2.75	6.00	11.50	14.00	22.25
0.50	147.00	1740	3480	35.6	35.6	2.75	6.00	11.50	14.00	22.25
1.50	148.50	5960	3970	40.6	40.6	2.75	6.00	11.50	14.00	22.25
0.50	149.00	2000	4000	40.9	40.9	2.75	6.00	11.50	14.00*	22.25
18.50	167.50	-	-	-	-	2.75	6.00	11.25	13.75	22.25
1.00	168.50	3800	3800	38.9	38.9	2.75	6.00	11.25	13.75	22.25
1.00	169.50	4000	4000	40.9	40.9	2.75	6.00	11.25	13.75*	22.25
1.00	170.50	4040	4040	41.4	41.4	2.75	6.00	11.50	14.00	22.25
0.50	171.00	2100	4200	43.0	43.0	2.75	6.00	11.75	14.00*	22.50
1.50	172.50	5860	3910	40.0	40.0	2.75	6.00	11.50	14.00	22.50
1.00	173.50	3930	3930	40.2	40.2	2.75	6.00	11.50	14.00	22.25
1.00	174.50	3970	3970	40.6	40.6	2.75	6.00	11.50	14.00	22.25
1.00	175.50	3940	3940	40.3	40.3	2.75	6.00	11.50	14.00	22.25
16.00	191.50	-	-	-	-	2.75	6.00	11.25	14.00	22.25
1.00	192.50	3920	3920	40.1	40.1	2.75	6.00	11.25	14.00	22.25
1.00	193.50	3900	3900	39.9	39.9	2.75	6.00	11.50	14.00	22.25
1.00	194.50	3910	3910	40.0	40.0	2.75	6.00	11.50	14.00	22.25
2.25	196.75	8800	3910	40.0	40.0	2.75	6.00	11.50	14.00	22.50
1.00	197.75	3800	3800	38.9	38.9	2.75	6.00	11.50	14.00	22.50
1.00	198.75	3900	3900	39.9	39.9	2.75	6.00	11.50	14.00	22.50
0.50	199.25	1940	3880	39.7	39.7	2.75	6.00	11.50	14.00	22.50

* Very slight leak noticeable at piezometer tube base.

APPENDIX VI

Hydraulic gradients within the sand column at specific time intervals (normal flow direction)

Depth boundaries of layers	0" -3"	3"-6"	6"-12"	12"-18"	18"-24"	24"-30"
Cumulative time (hrs.)						
20.00	0.33	0.75	1.13	0.54	1.46	1.33
40.00	0.42	0.58	0.88	0.50	1.46	1.63
60.00	0.50	0.75	0.67	0.42	1.46	1.79
80.00	0.67	0.83	0.67	0.38	1.38	1.83
100.00	0.83	1.00	0.79	0.38	1.17	1.67
120 .00	0.92	1.083	0.83	0.46	1.21	1.46
140.00	0.92	1.083	0.88	0.38	1.38	1.33
160.00	0.92	1.083	0.92	0.38	1.46	1.29
180.00	0.92	1.083	0.92	0.38	1.46	1.29
190.00	0.92	1.083	0.92	0.38	1.46	1.29
Mean hydr. gradient	0.74	0.93	0.86	0.42	1.39	1.49
S.E. of mean	± 0.075	± 0.059	± 0.011	± 0.019	± 0.035	± 0.069

APPENDIX VII (a)

Total pressure loss and flow data from a permeability experiment with core G_2 (normal flow direction)

Interval between readings (hrs.)	Cumulative time (hrs.)	Volume of leachate (mls.)	Flow rate (mls./hr.)	Flow rate (ins./hr.)	Hydr. Cond. 'k' (ins./hr.)	Total pressure losses at each depth							
						at 3" depth (ins.)	at 6" depth (ins.)	at 9" depth (ins.)	at 12" depth (ins.)	at 15" depth (ins.)	at 18" depth (ins.)	at 21" depth (ins.)	at 24" depth (ins.)
2.75	2.75	0.0	0.00	0.000	0.000	0.00	0.00	0.00	0.00	0.00	0.75	1.75	5.75
15.50	18.25	0.0	0.00	0.000	0.000	0.00	0.00	0.00	0.00	0.00	0.25	1.00	2.75
8.25	26.50	0.0	0.00	0.000	0.000	0.00	0.00	0.00	0.00	0.00	0.50	1.00	2.50
15.75	42.25	0.0	0.00	0.000	0.000	0.00	0.00	0.00	0.00	0.00	0.50	0.75	2.00
5.00	47.25	2.5	0.50	0.005	0.019	0.00	0.00	0.00	0.00	0.00	0.50	0.75	1.75
15.75	63.00*	14.0	0.89	0.0089	0.033	0.25	0.25	0.25	0.25	0.25	0.50	0.75	1.75
3.25	66.25	-	-	-	-	0.50	0.50	0.50	0.50	0.50	1.00	2.00	4.50
20.50	86.75	35.0	1.71	0.017	0.064	1.00	1.00	1.00	1.00	1.00	1.50	2.00	4.50
9.25	96.00	20.0	2.16	0.022	0.082	1.00	1.00	1.00	1.00	1.00	1.50	2.25	4.75
14.50	110.50	25.0	1.74	0.017	0.064	1.25	1.25	1.25	1.25	1.00	1.50	1.50	5.00
7.50	118.00	13.0	2.00	0.020	0.075	1.25	1.25	1.25	1.25	1.00	1.50	2.50	5.00
17.00	135.00	24.0	1.41	0.014	0.052	1.50	1.50	1.50	1.50	1.50	1.75	2.75	5.25
8.00	143.00	11.0	1.37	0.014	0.052	1.50	1.50	1.50	1.50	1.50	1.75	2.50	5.25
16.00	159.00	19.0	1.19	0.012	0.045	1.75	1.75	1.75	1.75	1.75	2.00	2.75	5.25
7.25	166.25	8.0	1.10	0.011	0.041	1.75	1.75	1.75	1.75	1.75	2.00	2.75	5.25
17.00	183.25	18.0	1.06	0.011	0.041	1.75	1.75	1.75	1.75	1.75	2.00	2.75	5.25
5.00	188.25	5.6	1.12	0.011	0.041	1.75	1.75	1.75	1.75	1.75	2.00	2.75	5.25

* A vacuum was applied to the effluent of the core immediately after this reading was taken.

APPENDIX VII(b)

Total pressure loss and flow data from a permeability experiment with core H_2

(normal flow direction)

Interval between readings (hrs.)	Cumulative time (hrs.)	Volume of leachate (mls.)	Flow rate (mls./hr.)	Flow rate (ins./hr.)	Hydr. Cond. 'k' (ins./hr.)	Total pressure losses at each depth							
						at 3" depth (ins.)	at 6" depth (ins.)	at 9" depth (ins.)	at 12" depth (ins.)	at 15" depth (ins.)	at 18" depth (ins.)	at 21" depth (ins.)	at 24" depth (ins.)
2.75	2.75	0.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.25	0.25
15.50	18.25	0.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.25
8.25	26.50	0.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.25	0.50
15.75	42.25	0.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.25	0.50
5.00	47.25	10.0	2.00	0.020	0.075	0.00	0.00	0.00	0.00	0.00	0.00	0.25	0.50
15.75	63.00*	36.5	2.32	0.023	0.086	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.75
3.25	66.25	62.0	19.10	0.19	0.71	0.50	0.75	0.75	1.00	1.25	1.50	2.25	4.75
20.50	86.75	370.0	18.06	0.18	0.67	0.50	0.75	0.75	1.00	1.00	1.50	2.00	4.50
9.25	96.00	125.0	13.50	0.14	0.52	0.50	0.75	0.75	0.75	1.00	1.25	1.75	4.50
14.50	110.50	150.0	10.30	0.10	0.37	0.75	0.75	0.75	0.75	0.75	1.00	1.50	4.00
7.50	118.00	60.0	8.00	0.080	0.30	0.75	0.75	0.75	0.75	0.75	0.75	1.25	3.75
17.00	135.00	105.0	6.20	0.062	0.23	0.75	0.75	0.75	0.75	0.75	0.75	1.25	3.50
8.00	143.00	43.0	5.40	0.054	0.20	0.75	0.75	0.75	0.75	0.75	0.75	1.00	3.25
16.00	159.00	77.0	4.40	0.044	0.17	0.75	0.75	0.75	0.75	0.75	0.75	1.00	3.25
7.25	166.25	33.0	4.55	0.046	0.17	0.75	0.75	0.75	0.75	0.75	0.75	1.00	3.00
17.00	183.25	71.5	4.20	0.042	0.16	0.75	0.75	0.75	0.75	0.75	0.75	1.00	2.75
5.00	188.25	21.7	4.34	0.043	0.16	0.75	0.75	0.75	0.75	0.75	0.75	1.00	2.75

* A vacuum was applied to the effluent of the core immediately after this reading was taken.

APPENDIX VII(c)

Total pressure loss and flow data from a permeability experiment with core I_2 (normal flow direction)

Interval between readings (hrs.)	Cumulative time (hrs.)	Volume of leachate (mls.)	Flow rate (mls./hr.)	Flow rate (ins./hr.)	Hydr. Cond. 'k' (ins./hr.)	Total pressure losses at each depth							
						at 3" depth (ins.)	at 6" depth (ins.)	at 9" depth (ins.)	at 12" depth (ins.)	at 15" depth (ins.)	at 18" depth (ins.)	at 21" depth (ins.)	at 24" depth (ins.)
2.75	2.75	0.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.25	1.25	2.00
15.50	18.25	0.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.25	1.00	1.75
8.25	26.50	3.5	0.42	0.0042	0.016	0.00	0.00	0.00	0.00	0.00	0.25	0.75	1.25
15.75	42.25	42.0	2.70	0.027	0.10	0.00	0.00	0.00	0.00	0.00	0.25	0.75	1.00
5.00	47.25	18.0	3.60	0.036	0.13	0.00	0.00	0.00	0.00	0.00	0.25	0.75	1.25
15.75	63.00*	64.0	4.10	0.041	0.15	0.00	0.00	0.00	0.00	0.00	0.25	0.75	1.25
3.25	66.25	61.0	18.80	0.19	0.71	0.25	0.25	0.25	0.50	0.75	1.25	3.50	5.25
20.50	86.75	360.0	17.50	0.18	0.67	0.25	0.25	0.50	0.50	0.75	1.25	4.00	6.00
9.25	96.00	125.0	13.50	0.14	0.52	0.25	0.25	0.25	0.50	0.50	1.25	4.00	6.00
14.50	110.50	170.0	11.70	0.12	0.45	0.25	0.25	0.25	0.50	0.50	1.25	4.00	6.25
7.50	118.00	82.0	10.90	0.11	0.41	0.25	0.25	0.25	0.25	0.50	1.00	4.00	6.00
17.00	135.00	152.0	9.00	0.090	0.34	0.25	0.25	0.25	0.25	0.50	1.00	3.75	6.00
8.00	143.00	66.0	8.30	0.083	0.31	0.25	0.25	0.25	0.25	0.50	0.75	3.75	5.75
16.00	159.00	115.0	7.20	0.072	0.27	0.25	0.25	0.25	0.25	0.50	0.75	3.25	5.25
7.25	166.25	52.0	7.20	0.072	0.27	0.25	0.25	0.25	0.25	0.50	0.75	3.00	5.00
17.00	183.25	118.0	6.90	0.069	0.26	0.25	0.25	0.25	0.25	0.50	0.75	2.50	4.50
5.00	188.25	34.0	6.80	0.068	0.25	0.25	0.25	0.25	0.25	0.50	0.75	2.50	4.25

* A vacuum was applied to the effluent of the core immediately after this reading was taken.

APPENDIX VII(d)

Total pressure loss and flow data from a permeability experiment with core J_2

(normal flow direction)

Interval between readings (hrs.)	Cumulative time (hrs.)	Volume of leachate (mls.)	Flow rate (mls./hr.)	Flow rate (ins./hr.)	Hydr. cond. 'k' (ins./hr.)	Total pressure losses at each depth							
						at 3" depth (ins.)	at 6" depth (ins.)	at 9" depth (ins.)	at 12" depth (Ins.)	at 15" depth (ins.)	at 18" depth (ins.)	at 21" depth (ins.)	at 24" depth (ins.)
2.75	2.75	0.0	0.00	0.00	0.00	9.25	9.25	9.25	9.25	9.25	9.25	9.25	9.25
15.50	18.25	0.0	0.00	0.00	0.00	7.75	7.75	7.75	7.75	7.75	9.25	9.25	9.25
8.25	26.50	0.0	0.00	0.00	0.00	6.50	6.50	6.50	6.50	6.50	7.75	9.25	9.25
15.75	42.25	0.0	0.00	0.00	0.00	5.25	5.25	5.25	5.25	5.25	5.75	6.50	7.50
5.00	47.25	0.0	0.00	0.00	0.00	4.50	4.50	4.50	4.50	4.50	4.75	5.00	5.50
15.75	63.00*	1.5	0.095	0.00095	0.0037	4.00	4.00	4.00	4.00	4.00	4.25	4.50	4.75
3.25	66.25	0.0	0.00	0.00	0.00	4.50	4.50	4.50	4.50	4.50	4.75	5.00	5.25
20.50	86.75	5.3	0.26	0.0026	0.010	5.50	5.50	5.50	5.50	5.50	5.50	5.75	6.25
9.25	96.00	3.0	0.32	0.0032	0.012	5.50	5.75	5.75	5.75	5.75	5.75	6.00	6.25
14.50	110.50	4.5	0.31	0.0031	0.012	5.50	5.50	5.50	5.50	5.50	5.50	5.75	6.25
7.50	118.00	2.0	0.27	0.0027	0.010	5.00	5.00	5.00	5.00	5.00	5.00	5.50	5.75
17.00	135.00	4.2	0.25	0.0025	0.0097	5.50	5.50	5.50	5.50	5.50	5.75	6.00	6.25
8.00	143.00	2.0	0.25	0.0025	0.0097	5.50	5.50	5.50	5.50	5.50	5.50	5.75	6.00
16.00	159.00	-	-	-	-	5.50	5.50	5.50	5.50	5.50	5.50	5.75	6.25
7.25	166.25	-	-	-	-	5.50	5.50	5.50	5.50	5.50	5.50	5.75	6.00
17.00	183.25	2.6	0.15	0.0015	0.0058	5.75	5.75	5.75	5.75	5.75	5.75	5.75	6.25
5.00	188.25	1.7	0.34	0.0034	0.013	5.50	5.50	5.50	5.50	5.50	5.50	5.75	6.00

* A vacuum was applied to the effluent of the core immediately after this reading was taken.

APPENDIX VII(e)

Total pressure loss and flow data from a permeability experiment with core K_2 (normal flow direction)

Interval between readings (hrs.)	Cumulative time (hrs.)	Volume of leachate (mls.)	Flow rate (mls./hr.)	Flow rate (ins./hr.)	Hydr. cond. 'k' (ins./hr.)	Total pressure losses at each depth							
						at 3" depth (ins.)	at 6" depth (ins.)	at 9" depth (ins.)	at 12" depth (ins.)	at 15" depth (ins.)	at 18" depth (ins.)	at 21" depth (ins.)	at 24" depth (ins.)
2.75	2.75	0.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.50	2.75	9.25
15.50	18.25	0.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	2.75
8.25	26.50	0.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.75	1.75
15.75	42.25	0.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.50	1.25
5.00	47.25	0.0	0.00	0.00	0.00	0.25	0.25	0.25	0.25	0.25	0.25	0.75	1.50
15.75	63.00*	13.5	0.86	0.0086	0.033	0.25	0.25	0.25	0.25	0.25	0.25	0.75	1.00
3.25	66.25	33.5	10.30	0.10	0.39	1.50	2.00	2.25	2.25	2.50	3.00	5.75	6.50
20.50	86.75	210.0	10.20	0.10	0.39	1.25	1.75	1.75	1.75	1.75	2.75	6.25	6.75
9.25	96.00	71.0	7.67	0.077	0.30	1.25	1.75	1.75	1.75	1.75	2.75	6.50	7.00
14.50	110.50	78.0	5.38	0.054	0.21	1.25	1.75	1.75	1.75	1.75	2.50	6.50	7.00
7.50	118.00	-	-	-	-	1.25	1.75	1.75	1.75	1.75	2.50	6.50	7.00
17.00	135.00	58.0	3.41	0.034	0.13	1.50	2.00	2.00	2.00	2.00	2.50	6.50	7.00
8.00	143.00	25.0	3.13	0.031	0.12	1.75	2.25	2.25	2.50	2.50	3.00	6.50	7.00
16.00	159.00	37.0	2.30	0.023	0.089	2.00	3.00	3.00	3.00	3.00	3.50	6.50	7.00
7.25	166.25	15.0	2.07	0.021	0.081	2.25	3.00	3.00	3.25	3.25	3.50	6.25	7.00
17.00	183.25	36.0	2.12	0.021	0.081	2.25	3.25	3.25	3.25	3.25	3.50	6.25	7.00
5.00	188.25	10.8	2.16	0.022	0.085	2.25	3.50	3.50	3.50	3.50	3.75	6.25	7.00

* A vacuum was applied to the effluent of the core immediately after this reading was taken.

APPENDIX VII(f)

Total pressure loss and flow data from a permeability experiment with core L_2 (normal flow direction)

Interval between readings (hrs.)	Cumulative time (hrs.)	Volume of leachate (mls.)	Flow rate (mls./hr.)	Flow rate (ins./hr.)	Hydr. cond. 'k' (ins./hr.)	Total pressure losses at each depth							
						at 3" depth (ins.)	at 6" depth (ins.)	at 9" depth (ins.)	at 12" depth (ins.)	at 15" depth (ins.)	at 18" depth (ins.)	at 21" depth (ins.)	at 24" depth (ins.)
2.75	2.75	0.0	0.00	0.00	0.00	0.00	0.00	0.00	0.25	0.25	0.25	1.00	2.75
15.50	18.25	87.0	5.60	0.056	0.22	0.00	0.25	0.25	0.25	0.25	0.25	0.50	1.25
8.25	26.50	49.0	5.80	0.058	0.22	0.00	0.25	0.25	0.25	0.25	0.25	0.50	1.25
15.75	42.25*	105.0	6.70	0.067	0.26	0.00	0.25	0.25	0.25	0.25	0.25	0.50	1.25
5.00	47.25	260.0	52.00	0.52	2.01	1.50	1.75	2.00	2.25	2.25	2.50	3.75	6.75
15.75	63.00	592.0	37.60	0.38	1.47	1.25	1.50	1.50	1.75	1.75	2.25	3.50	6.75
3.25	66.25	96.0	29.50	0.30	1.16	1.25	1.50	1.50	1.75	1.75	2.00	3.50	6.75
20.50	86.75	510.0	24.80	0.25	0.97	1.50	1.50	1.50	1.75	1.75	2.00	3.25	7.00
9.25	96.00	210.0	22.70	0.23	0.89	1.50	1.50	1.75	1.75	1.75	2.00	3.25	7.00
14.50	110.50	290.0	20.00	0.20	0.77	1.50	1.50	1.50	1.75	1.75	2.00	3.25	7.00
7.50	118.00	140.0	18.70	0.19	0.73	1.50	1.50	1.50	1.75	1.75	2.00	3.00	7.00
17.00	135.00	268.0	15.80	0.16	0.62	1.50	1.75	1.75	1.75	1.75	2.00	3.00	7.00
8.00	143.00	114.0	14.30	0.14	0.54	1.50	1.75	1.75	1.75	1.75	2.00	3.00	7.00
16.00	159.00	198.0	12.40	0.12	0.46	1.50	1.75	1.75	1.75	1.75	2.00	3.00	7.00
7.25	166.25	79.0	10.80	0.11	0.42	1.50	1.75	1.75	1.75	1.75	2.00	2.75	7.00
17.00	183.25	155.0	9.10	0.091	0.35	1.75	2.00	2.00	2.00	2.00	2.25	2.75	7.00
5.00	188.25	41.0	8.20	0.082	0.32	2.00	2.25	2.25	2.25	2.25	2.25	3.00	7.00

* A vacuum was applied to the effluent of the core immediately after this reading was taken.

APPENDIX VIII

Hydraulic gradients within core G_2 at specific time intervals (normal flow direction)

Depth boundaries of layers	0"-3"	3"-6"	6"-9"	9"-12"	12"-15"	15"-18"	18"-21"	21"-24"	24"-29"
Cumulative time (hrs.)									
86.75	0.33	0.00	0.00	0.00	0.00	0.17	0.17	0.83	0.65
96.00	0.33	0.00	0.00	0.00	0.00	0.17	0.25	0.83	0.60
110.50	0.42	0.00	0.00	0.00	0.00	0.083	0.33	0.83	0.55
118.00	0.42	0.00	0.00	0.00	0.00	0.083	0.33	0.83	0.55
135.00	0.50	0.00	0.00	0.00	0.00	0.083	0.33	0.83	0.50
143.00	0.50	0.00	0.00	0.00	0.00	0.083	0.25	0.92	0.50
159.00	0.58	0.00	0.00	0.00	0.00	0.083	0.25	0.83	0.50
166.25	0.58	0.00	0.00	0.00	0.00	0.083	0.25	0.83	0.50
183.25	0.58	0.00	0.00	0.00	0.00	0.083	0.25	0.83	0.50
188.25	0.58	0.00	0.00	0.00	0.00	0.083	0.25	0.83	0.50
Mean hydr. gradient	0.48	0.00	0.00	0.00	0.00	0.10	0.27	0.84	0.54
S.E. of mean	±0.036	±0.000	±0.000	±0.000	±0.000	±0.012	±0.016	±0.009	±0.017

APPENDIX IX

Hydraulic gradients within core H_2 at specific time intervals

(normal flow direction)

Depth boundaries of layers	0"-3"	3"-6"	6"-9"	9"-12"	12"-15"	15"-18"	18"-21"	21"-24"	24"-29"
Cumulative time (hrs.)									
86.75	0.17	0.083	0.00	0.083	0.00	0.17	0.17	0.83	0.65
96.00	0.17	0.083	0.00	0.00	0.083	0.083	0.17	0.92	0.65
110.50	0.25	0.00	0.00	0.00	0.00	0.083	0.17	0.83	0.75
118.00	0.25	0.00	0.00	0.00	0.00	0.00	0.17	0.83	0.80
135.00	0.25	0.00	0.00	0.00	0.00	0.00	0.17	0.75	0.85
143.00	0.25	0.00	0.00	0.00	0.00	0.00	0.083	0.75	0.90
159.00	0.25	0.00	0.00	0.00	0.00	0.00	0.083	0.75	0.90
166.25	0.25	0.00	0.00	0.00	0.00	0.00	0.083	0.67	0.95
183.25	0.25	0.00	0.00	0.00	0.00	0.00	0.083	0.58	1.00
188.25	0.25	0.00	0.00	0.00	0.00	0.00	0.083	0.58	1.00
Mean hydr. gradient	0.23	0.017	0.00	0.0083	0.0083	0.034	0.13	0.75	0.85
S.E. of mean	± 0.011	±0.011	±0.000	±0.026	±0.026	±0.019	±0.012	±0.035	±0.041

APPENDIX X

Hydraulic gradients within core I_2 at specific time intervals

(normal flow direction)

Depth boundaries of layers	0"-3"	3"-6"	6"-9"	9"-12"	12"-15"	15"-18"	18"-21"	21"-24"	24"-29"
Cumulative time (hrs.)									
86.75	0.083	0.00	0.083	0.00	0.083	0.17	0.92	0.67	0.35
96.00	0.083	0.00	0.00	0.083	0.00	0.25	0.92	0.67	0.35
110.50	0.083	0.00	0.00	0.083	0.00	0.25	0.92	0.75	0.30
118.00	0.083	0.00	0.00	0.00	0.083	0.17	1.00	0.67	0.35
135.00	0.083	0.00	0.00	0.00	0.083	0.17	0.92	0.75	0.35
143.00	0.083	0.00	0.00	0.00	0.083	0.083	1.00	0.67	0.40
159.00	0.083	0.00	0.00	0.00	0.083	0.083	0.83	0.67	0.50
166.25	0.083	0.00	0.00	0.00	0.083	0.083	0.75	0.67	0.55
183.25	0.083	0.00	0.00	0.00	0.083	0.083	0.58	0.67	0.65
188.25	0.083	0.00	0.00	0.00	0.083	0.083	0.58	0.58	0.70
Mean hydr. gradient	0.083	0.00	0.0083	0.017	0.066	0.14	0.84	0.68	0.45
S.E. of mean	± 0.000	±0.000	±0.026	±0.011	±0.011	±0.022	±0.049	±0.015	±0.045

APPENDIX XI

Hydraulic gradients within core K_2 at specific time intervals

(normal flow direction)

Depth boundaries of layers	0"-3"	3"-6"	6"-9"	9"-12"	12"-15"	15"-18"	18"-21"	21"-24"	24"-29"
Cumulative time (hrs.)									
86.75	0.42	0.17	0.00	0.00	0.33	0.00	1.17	0.50	1.00
96.00	0.42	0.17	0.00	0.00	0.33	0.00	1.25	0.17	0.75
110.50	0.42	0.17	0.00	0.00	0.25	0.00	1.33	0.17	0.75
118.00	0.42	0.17	0.00	0.00	0.25	0.00	1.33	0.17	0.75
135.00	0.50	0.17	0.00	0.00	0.17	0.00	1.33	0.17	0.75
143.00	0.58	0.17	0.00	0.083	0.17	0.00	1.17	0.17	0.75
159.00	0.67	0.33	0.00	0.00	0.17	0.00	1.00	0.17	0.75
166.25	0.75	0.25	0.00	0.083	0.083	0.00	0.92	0.25	0.75
183.25	0.75	0.33	0.00	0.00	0.083	0.00	0.92	0.25	0.75
188.25	0.75	0.42	0.00	0.00	0.083	0.00	0.83	0.25	0.75
Mean hydr. gradient	0.57	0.24	0.00	0.017	0.19	0.00	1.13	0.23	0.78
S.E. of mean	±0.047	±0.029	±0.000	±0.011	±0.030	±0.000	±0.061	±0.033	±0.025

APPENDIX XII

Hydraulic gradients within core L_2 at specific time intervals

(normal flow direction)

Depth boundaries of layers	0"-3"	3"-6"	6"-9"	9"-12"	12"-15"	15"-18"	18"-21"	21"-24"	24"-29"
Cumulative time (hrs.)									
86.75	0.50	0.00	0.00	0.083	0.00	0.083	0.42	1.25	0.75
96.00	0.50	0.00	0.083	0.083	0.00	0.083	0.42	1.25	0.75
110.50	0.50	0.00	0.00	0.083	0.00	0.083	0.42	1.25	0.75
118.00	0.50	0.00	0.00	0.083	0.00	0.083	0.33	1.33	0.75
135.00	0.50	0.083	0.00	0.00	0.00	0.083	0.33	1.33	0.75
143.00	0.50	0.083	0.00	0.00	0.00	0.083	0.33	1.33	0.75
159.00	0.50	0.083	0.00	0.00	0.00	0.083	0.33	1.33	0.75
166.25	0.50	0.083	0.00	0.00	0.00	0.083	0.25	1.42	0.75
183.25	0.58	0.083	0.00	0.00	0.00	0.083	0.17	1.42	0.75
188.25	0.67	0.083	0.00	0.00	0.00	0.00	0.17	1.33	0.75
Mean hydr. gradient	0.53	0.050	0.0083	0.033	0.00	0.075	0.32	1.32	0.75
S.E. of mean	±0.018	±0.014	±0.026	±0.014	±0.000	±0.0083	±0.030	±0.012	±0.000

APPENDIX XIII(a)

Total pressure loss and flow data from a permeability experiment with core G_2

(reversed flow direction)

Interval between readings (hrs.)	Cum. time (hrs.)	Vol. of lch'te (mls.)	Flow rate (mls./hr.)	Flow rate (ins./hr.)	Hydr. Cond. 'k' (ins./hr.)	Total pressure losses at each "depth"							
						at 24" "depth" (ins.)	at 21" "depth" (ins.)	at 18" "depth" (ins.)	at 15" "depth" (ins.)	at 12" "depth" (ins.)	at 9" "depth" (ins.)	at 6" "depth" (ins.)	at 3" "depth" (ins.)
1.75	1.75	0.0	0.00	0.00	0.00	2.25	6.50	8.00	9.50	9.50	9.50	9.50	9.50
15.75	17.50*	0.0	0.00	0.00	0.00	2.25	6.75	8.00	9.50	9.50	9.50	9.50	9.50
8.50	26.00	16.0	1.88	0.019	0.071	2.00	4.25	6.26	7.00	7.25	7.25	7.25	7.25
15.50	41.50	34.0	2.19	0.022	0.082	2.50	4.50	6.25	7.25	7.25	7.25	7.25	7.50
7.25	48.75	20.0	2.77	0.028	0.10	2.25	4.50	6.25	7.00	7.25	7.25	7.25	7.50
18.00	66.75	40.0	2.22	0.022	0.082	2.25	4.50	6.25	7.25	7.25	7.25	7.25	7.50
14.00	80.75	40.0	2.14	0.021	0.079	2.25	4.25	6.25	7.00	7.25	7.25	7.25	7.50
11.25	92.00	26.0	2.31	0.023	0.086	2.25	4.25	6.25	7.00	7.25	7.25	7.25	7.50
10.75	102.75	27.0	2.51	0.025	0.094	2.25	4.25	6.25	7.00	7.25	7.25	7.25	7.50
11.00	113.75	30.0	2.72	0.027	0.10	2.25	4.25	6.25	7.00	7.25	7.25	7.25	7.50
8.00	121.75	27.0	3.37	0.034	0.13	2.25	4.25	6.25	7.00	7.25	7.25	7.25	7.50
15.75	137.50	46.0	2.92	0.029	0.11	2.00	4.00	6.25	7.00	7.25	7.25	7.25	7.50
8.25	145.75	27.0	3.27	0.033	0.12	2.00	4.00	6.00	7.00	7.25	7.25	7.25	7.50
16.25	162.00	53.0	3.26	0.033	0.12	2.00	3.75	6.00	7.00	7.25	7.25	7.25	7.50
7.75	169.75	32.0	4.13	0.041	0.15	2.00	3.75	5.75	7.00	7.25	7.25	7.50	7.50
21.75	191.50	90.0	4.14	0.041	0.15	2.00	3.50	5.75	7.00	7.25	7.25	7.50	7.50

* A vacuum was applied to the effluent of the core immediately after this reading was taken.

APPENDIX XIII(b)

Total pressure loss and flow data from a permeability experiment with core H_2

(reversed flow direction)

Interval between readings (hrs.)	Cum. time (hrs.)	Vol. of lch'te (mls.)	Flow rate (mls./hr.)	Flow rate (ins./hr.)	Hydr. Cond. 'k' (ins./hr.)	Total pressure losses at each "depth"							
						at 24" "depth" (ins.)	at 21" "depth" (ins.)	at 18" "depth" (ins.)	at 15" "depth" (ins.)	at 12" "depth" (ins.)	at 9" "depth" (ins.)	at 6" "depth" (ins.)	at 3" "depth" (ins.)
1.75	1.75	0.0	0.00	0.00	0.00	6.25	7.75	8.00	8.00	8.25	8.25	8.25	9.50
15.75	17.50	30.0	1.91	0.019	0.071	5.75	7.00	7.50	7.50	7.50	7.50	7.50	8.00
8.50	26.00	25.0	2.94	0.029	0.11	5.75	7.00	7.25	7.50	7.50	7.50	7.50	7.75
15.50	41.50	46.0	2.98	0.030	0.11	5.75	7.00	7.25	7.50	7.50	7.50	7.50	7.75
7.25	48.75	25.0	3.45	0.035	0.13	5.75	7.00	7.25	7.50	7.50	7.50	7.50	7.75
18.00	66.75	52.0	2.89	0.029	0.11	5.75	7.00	7.25	7.25	7.50	7.50	7.50	7.75
14.00	80.75	38.0	2.71	0.027	0.10	5.75	7.00	7.25	7.25	7.50	7.50	7.50	7.75
11.25	92.00	30.0	2.67	0.027	0.10	5.75	7.00	7.25	7.25	7.25	7.25	7.25	7.75
10.75	102.75	30.0	2.79	0.028	0.10	5.75	7.00	7.25	7.25	7.25	7.25	7.25	7.75
11.00	113.75	31.5	2.86	0.029	0.11	5.75	7.00	7.25	7.25	7.25	7.25	7.25	7.75
8.00	121.75	27.0	3.38	0.034	0.13	5.75	6.50	6.75	6.75	6.75	6.75	7.00	7.50
15.75	137.50	44.0	2.79	0.028	0.10	5.50	6.25	6.50	6.50	6.50	6.75	6.75	7.00
8.25	145.75	22.0	2.67	0.027	0.10	5.25	6.25	6.50	6.75	6.75	6.75	6.75	7.00
16.25	162.00	53.0	3.26	0.033	0.12	5.50	6.50	6.75	6.75	6.75	6.75	7.00	7.00
7.75	169.75	32.0	4.13	0.041	0.15	5.00	6.00	6.25	6.50	6.50	6.50	6.50	7.00
21.75	191.50	103.0	4.74	0.047	0.18	4.50	5.50	5.75	6.00	6.00	6.00	6.25	6.75

APPENDIX XIII(c)

Total pressure loss and flow data from a permeability experiment with core I_2

(reversed flow direction)

Interval between readings (hrs.)	Cum. time (hrs.)	Vol. of lch'te (mls.)	Flow rate (mls./hr.)	Flow rate (ins./hr.)	Hydr. cond. 'k' (ins./hr.)	Total pressure losses at each "depth"							
						at 24" "depth" (ins.)	at 21" "depth" (ins.)	at 18" "depth" (ins.)	at 15" "depth" (ins.)	at 12" "depth" (ins.)	at 9" "depth" (ins.)	at 6" "depth" (ins.)	at 3" "depth" (ins.)
1.75	1.75	0.0	0.00	0.00	0.00	3.00	4.50	6.50	6.75	6.75	7.00	7.00	7.00
15.75	17.50	60.0	3.81	0.038	0.14	2.50	3.75	5.50	5.75	5.75	5.75	5.75	6.00
8.50	26.00	47.0	5.54	0.055	0.21	2.25	3.25	5.00	5.50	5.50	5.50	5.75	5.75
15.50	41.50	105.0	6.77	0.068	0.25	2.25	3.25	5.00	5.25	5.50	5.50	5.50	5.75
7.25	48.75	68.0	9.38	0.094	0.35	2.25	3.00	5.00	5.25	5.25	5.50	5.50	5.75
18.00	66.75	187.0	10.39	0.10	0.37	2.25	3.00	5.00	5.25	5.25	5.50	5.50	5.75
14.00	80.75	173.0	12.36	0.12	0.45	2.25	3.00	4.75	5.25	5.25	5.50	5.50	5.75
11.25	92.00	145.0	12.89	0.13	0.49	2.50	3.00	4.75	5.25	5.25	5.50	5.50	5.75
10.75	102.75	150.0	13.95	0.14	0.52	2.75	3.25	5.00	5.25	5.50	5.50	5.50	6.00
11.00	113.75	166.0	15.09	0.15	0.56	2.75	3.25	5.00	5.25	5.50	5.50	5.50	6.00
8.00	121.75	131.0	16.38	0.16	0.60	2.75	3.25	5.00	5.25	5.50	5.50	5.75	6.00
15.75	137.50	225.0	14.29	0.14	0.52	3.50	3.75	5.25	5.50	5.50	5.75	5.75	6.00
8.25	145.75	109.0	13.21	0.13	0.49	3.50	3.75	5.25	5.50	5.50	5.75	5.75	6.00
16.25	162.00	209.0	12.86	0.13	0.49	3.75	4.25	5.25	5.50	5.50	5.75	5.75	6.25
7.75	169.75	100.0	12.90	0.13	0.49	4.00	4.25	5.25	5.50	5.50	5.75	5.75	6.00
21.75	191.50	260.0	11.95	0.12	0.45	4.25	4.50	5.50	5.75	5.75	5.75	5.75	6.25

APPENDIX XIII(d)

Total pressure loss and flow data from a permeability experiment with core J_2

(reversed flow direction)

Interval between readings (hrs.)	Cum. time (hrs.)	Vol. of lch'te (mls.)	Flow rate (mls./hr.)	Flow rate (ins./hr.)	Hydr. cond. 'k' (ins./hr.)	Total pressure losses at each "depth"							
						at 24" "depth" (ins.)	at 21" "depth" (ins.)	at 18" "depth" (ins.)	at 15" "depth" (ins.)	at 12" "depth" (ins.)	at 9" "depth" (ins.)	at6" "depth" (ins.)	at 3" "depth" (ins.)
1.75	1.75	0.0	0.00	0.00	0.00	4.75	7.25	8.00	8.25	8.25	8.25	8.50	8.50
15.75	17.50*	0.0	0.00	0.00	0.00	4.75	5.50	6.00	6.50	6.50	6.50	6.50	6.75
8.50	26.00	5.0	0.059	0.00059	0.0023	5.50	6.50	6.75	6.75	7.00	7.00	7.00	7.00
15.50	41.50	8.0	0.052	0.00052	0.0020	5.75	6.50	6.75	6.75	7.00	7.00	7.00	7.00
7.25	48.75	4.6	0.064	0.00064	0.0025	5.75	6.50	6.75	6.75	7.00	7.00	7.00	7.00
18.00	66.75	8.5	0.047	0.00047	0.0018	5.75	6.50	6.75	6.75	7.00	7.00	7.00	7.00
14.00	80.75	4.4	0.031	0.00031	0.0012	6.00	6.25	6.75	6.75	6.75	6.75	6.75	7.00
11.25	92.00	3.2	0.028	0.00028	0.0011	5.75	6.00	6.25	6.25	6.25	6.25	6.25	6.50
10.75	102.75	3.1	0.029	0.00029	0.0011	5.75	6.00	6.50	6.50	6.50	6.50	6.50	6.50
11.00	113.75	3.2	0.029	0.00029	0.0011	5.75	6.00	6.50	6.50	6.50	6.50	6.50	6.50
8.00	121.75	3.8	0.048	0.00048	0.0019	5.25	5.75	6.00	6.00	6.00	6.00	6.25	6.25
15.75	137.50	2.9	0.018	0.00018	0.00069	4.50	4.75	5.00	5.00	5.00	5.00	5.00	5.25
8.25	145.75	4.3	0.052	0.00052	0.0020	4.75	5.25	5.50	5.50	5.50	5.50	5.75	5.75
16.25	162.00	2.2	0.015	0.00015	0.00058	4.75	5.00	5.25	5.25	5.25	5.25	5.25	5.50
7.75	169.75	2.8	0.036	0.00036	0.0014	4.50	4.75	5.00	5.00	5.00	5.00	5.00	5.00
21.75	191.50	7.7	0.035	0.00035	0.0014	4.50	4.75	5.00	5.00	5.00	5.00	5.00	5.25

* A vacuum was applied to the effluent of the core immediately after this reading was taken.

APPENDIX XIII(e)

Total pressure loss and flow data from a permeability experiment with core K_2

(reversed flow direction)

Interval between readings (hrs.)	Cum. time (hrs.)	Vol. of lch'te (mls.)	Flow rate (mls./hr.)	Flow rate (ins./hr.)	Hydr. cond. 'k' (ins./hr.)	Total pressure losses at each "depth"							
						at 24" "depth" (ins.)	at 21" "depth" (ins.)	at 18" "depth" (ins.)	at 15" "depth" (ins.)	at12" "depth" (ins.)	at 9" "depth" (ins.)	at 6" "depth" (ins.)	at 3" "depth" (ins.)
1.75	1.75	0.0	0.00	0.00	0.00	1.00	2.25	6.25	7.50	7.50	7.50	7.50	8.75
15.75	17.50	30.5	1.94	0.019	0.073	0.75	2.00	5.00	6.00	6.00	6.00	6.00	6.25
8.50	26.00	35.0	4.11	0.041	0.16	0.75	1.75	4.50	5.25	5.50	5.50	5.75	6.00
15.50	41.40	91.0	5.87	0.059	0.23	0.50	1.75	4.25	5.25	5.50	5.50	5.75	6.00
7.25	48.75	64.0	8.82	0.082	0.32	0.50	1.75	3.75	4.75	5.00	5.00	5.25	5.75
18.00	66.75	218.0	12.20	0.12	0.46	0.50	1.50	3.50	4.75	5.00	5.00	5.25	5.75
14.00	80.75	250.0	17.86	0.18	0.69	0.50	1.50	3.50	5.00	5.25	5.25	5.50	6.00
11.25	92.00	247.0	21.96	0.22	0.85	0.50	1.50	3.50	5.00	5.25	5.50	5.75	6.00
10.75	102.75	265.0	24.65	0.25	0.97	0.75	1.50	3.50	5.00	5.50	5.50	5.75	6.00
11.00	113.75	300.0	27.27	0.27	1.04	0.75	1.50	3.50	5.00	5.50	5.50	5.75	6.00
8.00	121.75	240.0	30.00	0.30	1.16	0.75	1.50	3.25	5.00	5.50	5.50	5.75	6.00
15.75	137.50	470.0	29.84	0.30	1.16	0.75	1.50	3.00	4.75	5.00	5.25	5.50	5.75
8.25	145.75	250.0	30.30	0.30	1.16	0.75	1.50	2.75	4.50	4.75	5.00	5.25	5.75
16.25	162.00	760.0	46.77	0.47	1.81	0.75	1.50	2.75	4.50	5.00	5.25	5.50	5.75
7.75	169.75	310.0	40.00	0.40	1.54	0.75	1.50	2.50	4.25	4.75	5.00	5.25	5.75
21.75	191.50	880.0	40.46	0.40	1.54	0.75	1.50	2.25	3.75	4.25	4.50	4.75	5.25

APPENDIX XIII(f)

Total pressure loss and flow data from a permeability experiment with core L_2

(reversed flow direction)

Interval between readings (hrs.)	Cum. time (hrs.)	Vol. of lch'te (mls.)	Flow rate (mls./hr.)	Flow rate (ins./hr.)	Hydr. cond. 'k' (ins./hr.)	Total pressure losses at each "depth"							
						at 24" "Depth" (ins.)	at 21" "depth" (ins.)	at 18" "depth" (ins.)	at 15" "depth" (ins.)	at 12" "depth" (ins.)	at 9" "depth" (ins.)	at 6" "depth" (ins.)	at 3" "depth" (ins.)
1.75	1.75	8.5	4.90	0.049	0.19	0.00	2.00	3.00	3.00	3.00	3.00	3.25	3.50
15.75	17.50	104.0	6.60	0.066	0.25	0.00	2.00	2.50	2.50	2.50	2.50	2.75	3.00
8.50	26.00	63.0	7.40	0.074	0.28	0.00	1.50	2.00	2.00	2.00	2.00	2.25	2.50
15.50	41.50	115.0	7.42	0.074	0.28	0.00	1.00	1.50	1.50	1.50	1.50	1.75	2.00
7.25	48.75	59.0	8.14	0.081	0.31	0.00	0.75	1.00	1.00	1.00	1.00	1.25	1.50
18.00	66.75*	131.0	7.26	0.073	0.28	0.00	0.75	0.75	0.75	0.75	0.75	1.00	1.25
14.00	80.75	-	-	-	-	1.00	3.50	4.25	4.25	5.00	5.25	5.50	6.50
11.25	92.00	1310.0	116.44	1.16	4.48	1.00	4.00	4.50	5.00	5.25	5.50	5.75	6.50
10.75	102.75	1100.0	102.32	1.02	3.93	0.75	4.00	4.75	5.00	5.25	5.50	6.00	6.75
11.00	113.75	1010.0	91.81	0.92	3.55	0.75	4.25	5.00	5.25	5.50	5.75	6.00	6.75
8.00	121.75	700.0	87.50	0.88	3.40	0.50	4.25	5.00	5.25	5.50	5.50	6.00	6.75
15.75	137.50	1240.0	78.73	0.79	3.05	0.50	4.50	5.00	5.25	5.50	5.75	6.00	6.75
8.25	145.75	620.0	75.15	0.75	2.90	0.50	4.50	5.00	5.25	5.50	5.75	6.00	6.75
16.25	162.00	1205.0	74.15	0.74	2.86	0.50	4.25	5.00	5.00	5.25	5.50	6.00	6.50
7.75	169.75	555.0	71.61	0.72	2.78	0.50	4.25	4.75	5.00	5.25	5.50	6.00	6.50
21.75	191.50	1510.0	69.43	0.69	2.66	0.50	4.00	4.75	5.00	5.00	5.50	5.75	6.50

* A vacuum was applied to the effluent of the core immediately after this reading was taken.

APPENDIX XIV

Hydraulic gradients within core G_2 at specific time intervals (reversed flow direction)

"Depth" boundaries of layers	29"-24"	24"-21"	21"-18"	18"-15"	15"-12"	12"-9"	9"-6"	6"-3"	3"-0"
Cumulative time (hrs.)									
41.50	0.50	0.67	0.58	0.33	0.00	0.00	0.00	0.083	0.083
48.75	0.45	0.75	0.58	0.25	0.083	0.00	0.00	0.083	0.083
66.75	0.45	0.75	0.58	0.33	0.00	0.00	0.00	0.083	0.083
80.75	0.45	0.67	0.67	0.25	0.083	0.00	0.00	0.083	0.083
92.00	0.45	0.67	0.67	0.25	0.083	0.00	0.00	0.083	0.083
102.75	0.45	0.67	0.67	0.25	0.083	0.00	0.00	0.083	0.083
113.75	0.45	0.67	0.67	0.25	0.083	0.00	0.00	0.083	0.083
121.75	0.45	0.67	0.67	0.25	0.083	0.00	0.00	0.083	0.083
137.50	0.40	0.67	0.75	0.25	0.083	0.00	0.00	0.083	0.083
145.75	0.40	0.67	0.67	0.33	0.083	0.00	0.00	0.083	0.083
162.00	0.40	0.58	0.75	0.33	0.083	0.00	0.00	0.083	0.083
169.75	0.40	0.58	0.67	0.42	0.083	0.00	0.083	0.00	0.083
191.50	0.40	0.50	0.75	0.42	0.083	0.00	0.083	0.083	0.083
Mean hydr. gradient	0.43	0.66	0.67	0.30	0.070	0.00	0.013	0.077	0.083
S.E. of mean	± 0.0087	±0.019	±0.017	±0.018	±0.0087	±0.000	±0.0086	±0.0084	±0.000

APPENDIX XV

Hydraulic gradients within core H_2 at specific time intervals (reversed flow direction)

"Depth" boundaries of layers	29"-24"	24"-21"	21"-18"	18"-15"	15"-12"	12"-9"	9"-6"	6"-3"	3"-0"
Cumulative time (hrs.)									
41.50	1.15	0.42	0.083	0.083	0.00	0.00	0.00	0.083	0.00
48.75	1.15	0.42	0.083	0.083	0.00	0.00	0.00	0.083	0.00
66.75	1.15	0.42	0.083	0.00	0.083	0.00	0.00	0.083	0.00
80.75	1.15	0.42	0.083	0.00	0.083	0.00	0.00	0.083	0.00
92.00	1.15	0.42	0.083	0.00	0.00	0.00	0.00	0.17	0.00
102.75	1.15	0.42	0.083	0.00	0.00	0.00	0.00	0.17	0.00
113.75	1.15	0.42	0.083	0.00	0.00	0.00	0.00	0.17	0.00
121.75	1.15	0.42	0.083	0.00	0.00	0.00	0.083	0.17	0.083
135.50	1.10	0.25	0.083	0.00	0.00	0.083	0.00	0.083	0.25
145.75	1.05	0.25	0.083	0.083	0.00	0.00	0.00	0.083	0.25
162.00	1.10	0.33	0.083	0.00	0.00	0.00	0.083	0.00	0.25
169.75	1.00	0.33	0.083	0.083	0.00	0.00	0.00	0.17	0.25
191.50	0.90	0.33	0.083	0.083	0.00	0.00	0.083	0.17	0.33
Mean hydr. gradient	1.10	0.37	0.083	0.032	0.013	0.0064	0.019	0.12	0.11
S.E. of mean	± 0.022	± 0.019	±0.000	± 0.012	±0.0086	±0.0032	±0.010	±0.016	±0.037

APPENDIX XVI

Hydraulic gradients within core I_2 at specific time intervals (reversed flow direction)

"Depth" boundaries of layers	29"-24"	24"-21"	21"-18"	18"-15"	15"-12"	12"-9"	9"-6"	6"-3"	3"-0"
Cumulative time (hrs.)									
41.50	0.45	0.33	0.58	0.083	0.083	0.00	0.00	0.083	0.67
48.75	0.45	0.25	0.67	0.083	0.00	0.083	0.00	0.083	0.67
66.75	0.45	0.25	0.67	0.083	0.00	0.083	0.00	0.083	0.67
80.75	0.45	0.25	0.58	0.17	0.00	0.083	0.00	0.083	0.67
92.00	0.50	0.17	0.58	0.17	0.00	0.083	0.00	0.083	0.67
102.75	0.55	0.17	0.58	0.083	0.083	0.00	0.00	0.17	0.58
113.75	0.55	0.17	0.58	0.083	0.083	0.00	0.00	0.17	0.58
121.75	0.55	0.17	0.58	0.083	0.083	0.00	0.083	0.083	0.58
137.50	0.70	0.083	0.50	0.083	0.00	0.083	0.00	0.083	0.58
145.75	0.70	0.083	0.50	0.083	0.00	0.083	0.00	0.083	0.58
162.00	0.75	0.17	0.33	0.083	0.00	0.083	0.00	0.17	0.50
169.75	0.80	0.083	0.33	0.083	0.00	0.083	0.00	0.083	0.58
191.50	0.85	0.083	0.33	0.083	0.00	0.00	0.00	0.17	0.50
Mean Hydr. gradient	0.60	0.17	0.52	0.096	0.026	0.051	0.0064	0.11	0.60
S.E. of mean	± 0.040	± 0.022	± 0.034	± 0.0091	± 0.011	± 0.012	± 0.0032	± 0.012	± 0.017